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LARGE-SCALE CARBON FIBER TESTS

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LARGE-SCALE CARBON FIBER TESTS

by

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SUMMARY

A realistic release of carbon fibers was established by burning a minimum of 45 kg of carbon-fiber composite aircraft structural components in each of five large-scale, outdoor aviation jet fuel fire tests conducted at the U.S. Army Dugway Proving Ground, Utah. This release was quantified by several independent assessments with various instruments developed specifically for these tests. The most likely values for the mass of single carbon fibers released ranged from 0.2 percent of the initial mass of carbon fiber for the source tests (zero wind velocity) to a maximum of 0.6 percent of the initial carbon fiber mass for dissemination tests (5 - 6 m/s wind velocity). Mean fiber lengths for fibers greater than 1 mm in length ranged from 2.5 to 3.5 mm. Mean diameters ranged from 3.6 to 5.3 μm which was indicative of significant oxidation. Footprints of downwind dissemination of the fire-released fibers were measured to 19.1 km from the fire. The tests demonstrated a reasonable validation of the assumed carbon fiber lengths and quantity released that were used in the NASA risk assessment.

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INTRODUCTION

Carbon fibers have high strength and stiffness and are lightweight, making them very attractive for use in composite structures. The fibers also have high electrical conductivity such that when free carbon fibers settle on electrical conductors, they can cause equipment malfunctions or damage from short circuiting. As long as the fibers are embedded in the matrix of a composite material, they pose no hazard. However, when the composite is burned, as may occur in an aircraft crash-fire accident, fibers can be released from the matrix, become airborne, and be disseminated over large areas, creating a potential hazard to electrical and electronic equipment. The Graphite Fibers Risk Analysis Program Office at Langley Research Center has been charged with assessing the risk associated with such an accidental release of carbon fiber.

The release of carbon fibers from burning carbon composites has been quantified in nearly three hundred laboratory experiments (ref. 1). The amount of fiber released was found to be relatively low, usually less than one percent of the fiber-available in the original composite unless the burning debris was disturbed with explosive force. The first large-scale outdoor tests designed to verify the laboratory release of carbon fibers from burning composites were conducted in 1978 for the military at the Naval Weapons Center, China Lake, California. The test data were reduced, analyzed, and reported (ref. 2) through a contract from NASA. The very small amounts of single carbon fibers found in the samples were conceded to have been the result of the fire plume lofting most of the released fibers over and beyond the fiber samplers.

Subsequently, another series of large-scale outdoor aviation jet fuel fire tests were designed with more suitable collector locations in order to demonstrate a more realistic measure of the release of carbon fiber from burning composites in an aircraft crash-and-burn scenario. These tests were conducted at the U.S. Army Dugway Proving Ground, Utah, and benefited from the earlier experiences with outdoor fire testing, as well as from Dugway's background with airborne particle dissemination. In order to establish several independent assessments of the amount and size spectra of fire-released fibers, several types of fire plume sampling instruments were designed and employed. Instrumentation was also deployed ten times farther downwind than in prior carbon fiber tests in order to more adequately determine fiber dissemination patterns.

Preliminary results of the Dugway tests were presented in an industry/government briefing held at Langley Research Center December 4-5, 1979, (ref. 3). Results based on data from the individual sampling systems are presented in reports by the responsible organizations (refs. 4-6). This report summarizes the large-scale tests, presents results not otherwise reported, and compares fiber data from each of the sampling systems. In addition, the behavior of composite aircraft structural parts located in or near the fire was studied and the results are discussed.

Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

TEST DESIGN

The large-scale outdoor aviation jet fuel fire tests were designed to be representative of the average fuel-fed fire occurring in the United States from commercial aircraft accidents (ref. 7) over the last ten years. Although individual accidents exhibited large variations in the size and duration of the fire and in the amount of fuel burned, average values were approximately 20 minutes duration and 11,400 litres (3000 gallons) of jet fuel. Restricting the size of the fire to a pool which would burn at an essentially constant rate was considered to be most severe in terms of its effect on nearby composite structure. Large open pools of aviation jet fuel burn at a depth recession rate of about 6 mm per minute, thus for a 20-minute fire with 11,400 litres of fuel, a pool depth of 12 cm and a pool diameter of 10.7 m were required. Based on early analytical modeling (ref. 8) this diameter was sufficient to provide reasonable-sized regions of high temperature and fire-plume velocities associated with large fires. Two types of fire tests were planned; one with ambient wind velocity essentially zero, and one with winds of 3-6 m/s which would tilt the fire plume and produce a downwind deposition footprint.

The mass of carbon-fiber composite material required to be burned in a test was selected based on an assumed single fiber release of one percent of the fiber in the composite, downwind deposition footprints (ref. 9) predicted from existing airborne particle dissemination methodology, and sampling instrumentation detection limits. A minimum of

45 kg (100 lb) of composite was calculated as necessary to be burned in order to expect to detect a downwind footprint at a value of deposition equal to one-tenth of the peak deposition.

The establishment of the downwind ground sampling lines (figure 1) was designed to take advantage of the existing grid system for sampling at Dugway and the available historical meteorological data. The Dugway sampling area is located on a flat, dry-lake bed in a valley bounded on the sides by mountain ranges approximately 20 km apart running northwest to southeast. The greatest frequency of occurrence of any steady wind direction was for postfrontal northwest winds which could be expected to remain within an azimuth variation of plus or minus 35 degrees.

Twelve sampling lines were established by Dugway for these tests (fig. 1) ranging from a circle with a 91.4 m radius around the fire pool to a line perpendicular to the design wind direction and 19100 m downwind. Sampler instrumentation was located along these lines at spacings varying from 4 m to 274 m. Details are given in reference 4.

The design for independent assessments of the source strength of fire-released single carbon fibers was based on the proposed development of fire-plume sampling instrumentation which could operate in the hot environmental close to the end of the visible flame in the plume. An overhead canopy of steel cables (fig. 2) was designed by Dugway to be suspended from four 60 m high towers. Sixty-one canister collectors were being from this canopy in a pattern designed to sample much of the fire plume as it rose from the fire pool. The canopy could be raised

or lowered by winches at each of the towers in order to position the samplers in an optimum location for the wind conditions in each test. Design wind conditions for the downwind dissemination tests required a fire pool to be located on the ground close to the upwind side of the overhead canopy (fig. 2) in order for the tilted plume to pass through the canopy. A second fire pool was located beneath the center of the canopy to be used for source tests when the wind velocity was essentially zero. Figure 3 is a photograph of the overhead canopy suspended from the four towers about 40 m above ground level at sunrise on one of the test days.

A vertical array of stainless steel mesh samplers was designed by Dugway to be suspended from cables located vertically between the ground and a catenary cable stretched between the tops of the two downwind towers (fig. 2). This vertical array of instrumentation was also designed to intercept much of the tilted fire plume in the dissemination tests and to provide a second assessment of the source strength of single fibers.

TRW, Inc. designed, fabricated and operated under NASA contract a balloon-supported Jacob's ladder sampling system (fig. 4) which provided a third assessment of the source strength (ref. 5). The concept was a large 305 m square net located 140 m downwind from the fire; far enough for the plume to have cooled sufficiently to allow normal ambient air sampling equipment to be used, but close enough to the fire to provide a reasonable chance to intercept most of the expanding plume. The sampling net was suspended from a catenary cable which was in turn suspended from two blimp-type balloons. The system was stabilized by

anchor lines and tether lines out to the sides, the front and the rear. The entire system was constructed with Kevlar cables to minimize weight. Distances from the net to the side and forward tether anchors were greater than one km. The Washington Monument is drawn to scale in figure 4 to provide a sense of the size of this sampling net.

In normal operations between fire tests the Jacob's ladder net was laid down on a rope table on the ground downwind of the erected position. Prior to each test, instrumentation was attached to the net, the balloons were inflated, and the entire system was raised to the operating position. The detailed procedure is given in reference 5. The two balloons were furnished by the U.S. Air Force Geophysics Laboratory and were operated by two of their balloon handling crews. The 27 m long balloons are shown in figure 5 flying on short tether lines prior to being attached to the Jacob's ladder.

One quadrant of the Jacob's ladder net with one of the two balloons is shown in figure 6 as it appeared during one of the test times when the net was raised. The net lines create 15 m squares with fiber sampling instrumentation attached at each intersection. Total net instrumentation was designed to a weight goal so as not to exceed the available lift capability of the two balloons. Servicing of the instrumentation had to be done while the net was laid down on the ground table between tests.

TEST INSTRUMENTATION

A major consideration in the design of the outdoor aviation jet fuel fire tests was the capability of available instrumentation to detect and quantify the presence of single carbon fibers released from the burning composite material. Several new instruments were developed to collect fibers in the fire plume close to the source and to determine the rate of fiber release. Each type of instruments used successfully in these tests is described in the following sections. An overview of all the instrumentation is given in table I.

Stainless Steel Canister Collector

The stainless steel canister collector was a passive, trap-like sampler (fig. 7) designed by Dugway to provide isokinetic sampling of the fire plume just beyond the visible flames over the outdoor pool fires (ref. 10).

The collector was designed to trap emitted carbon fibers as the rising plume gases and fibers enter the sampler nozzle, pass into the fiber entrapment screen where fibers of lengths greater than approximately one mm are retained, and the plume gases are passed on through the sampler exhaust. The stainless steel outer shell enclosed a 46 cm long, 20 cm diameter cylindrical entrapment screen of stainless steel woven wire mesh (0.36 mm diameter wires spaced 1.06 mm on centers). The area of the entrapment screen is considerably greater than the area of the entrance nozzle (4.8 cm diameter), thus minimizing the soot saturation problem common to the other types of samplers working close to the fire.

The canister collector was calibrated in several wind tunnels. Airflow through the nozzle was near isokinetic and carbon fiber collection efficiency was 0.94. A cosine correction for plume direction relative to canister orientation was verified.

Sixty-one of these stainless steel canister collectors were suspended from the overhead canopy cables (figs. 2 and 3) for each of the fire tests. Carbon fibers were recovered after each test from the entrapment screens by "air washing" the screen into a cylindrical container equipped with a mesh filter and a vacuum line (ref. 10). Test residue was collected on the mesh filter, transferred to a sticky paper approximately 10 cm square, and examined under a microscope for carbon fibers.

Stainless Steel Mesh Can Sampler

The stainless steel mesh can sampler (fig. 8) was designed by Dugway to sample in the hat plume as it passed through a vertical array 58 m downwind from the fire. The samplers consisted of a seamless cylinder of electrolytic tin plate, 5.7 cm long and 9.5 cm diameter, with one edge curled. Stainless steel wire cloth (0.46 mm diameter wires spaced 1.59 mm on centers) was stretched across the curled edge and spot-welded to the side of the cylinder. A silicone grease, formulated to maintain its consistency from -240°C to 260°C , was coated onto the stainless steel mesh to ensure carbon fiber adhesion in the high temperature plume gases.

A post-test field calibration with 5 mm long chopped virgin carbon fibers indicated a collection efficiency of 0.54. Slippage of short

fibers through the stainless steel mesh when challenged with a spectrum of fiber lengths was assumed to be the same as had been previously established for the nylon mesh can samplers.

Nylon Mesh Can Sampler

The nylon mesh can sampler (fig. 9) was the standard airborne particle sampler developed and used by Dugway for several years. It consisted of a wax-coated paperboard cylinder 6.4 cm long and 8.6 cm diameter, with nylon mesh (bridal veil with threads spaced 1.50 mm on centers) stretched across one end and fastened to the side of the cylinder with kraft adhesive paper tape. To ensure adhesion of fibers to the sampler, the mesh was dipcoated in a mixture consisting of 3 percent lanolin and 4 percent mineral oil in a freon 113 base.

Calibration of the nylon mesh can sampler had been conducted in a wind tunnel (ref. 11) and established a carbon fiber collection efficiency of 1.00 for fibers with lengths greater than 5 mm. Slippage factors through the nylon mesh for carbon fibers 1-2 mm and 2-3 mm long were 15.6 and 8.8 percent, respectively, as established by wind tunnel tests with a spectrum of fiber lengths.

Nylon mesh can samplers were used primarily on the ground-supported downwind sampling lines (fig. 1), attached to stakes 0.5 m above the ground surface with the nylon mesh in a vertical plane perpendicular to the design wind direction. Nylon mesh cans were also used on the Jacob's ladder in one test for comparison with other fiber sampling instruments. The location of all of the instrumentation used on the Jacob's ladder is shown in figure 10.

Nylon Mesh Vu-graph Sampler

The nylon mesh vu-graph sampler (figs. 9 and 10) was the primary fiber sampler used on the Jacob's ladder. It was developed by TRW and was used initially in the outdoor fire-released carbon fiber tests at China Lake (ref. 2). The sampler consisted of a swatch of nylon bridal veil netting (mesh opening approximately 1 mm) stretched across and fastened to the edges of a vu-graph frame. The fiber collection area was 19 cm wide by 24 cm long. Prior to a test the nylon mesh was sprayed on the up-wind surface with Rhoplex, a nondrying, commercially available adhesive which had the unique property of remaining sticky for several days under all encountered weather conditions of wind, temperature, water, and solar radiation.

The nylon mesh vu-graph sampler has never been calibrated for fiber collection efficiency. It has been assumed to function in a similar manner to the nylon mesh can, and the same slippage factors for short fibers were applied in all of the data reduction. A discussion of the collection efficiency is included in a later section.

Cardboard Canister Collector

The cardboard canister collector (figs. 9 and 10) was a smaller adaptation of the Dugway stainless steel canister collector. The smaller cardboard adaptation was designed by NASA as a lightweight version which could be attached to the Jacob's ladder at numerous locations. It was equipped with tail fins to keep the index nozzle pointed into the wind. Detailed dimensions are shown in figure 11. After each test the canister screens were taken apart and the surfaces

were air-washed into a container equipped with a mesh filter and a vacuum line in the same manner as the larger stainless steel canister collectors.

The cardboard canister collector was calibrated in the NASA-Langley free flight wind tunnel at air speeds up to 18 m/s and at angles of attack up to 20° . Air sampling efficiency was slightly less than isokinetic and non-linear at the higher velocities, for example, 0.83 at 3 m/s and 0.70 at 6 m/s. This performance probably was due to the change in location of the exhaust parts on the canister from the rear end to the sides behind the conical section. This same NASA adaptation of the canister collector was used previously in fire-released carbon fiber tests in the shock tube at the U.S. Naval Surface Weapons Center - Dahlgren Laboratory (ref. 12).

Charged Grid Detector

The charged grid detector (figs. 9 and 10) consisted of a wire comb assembly made of a number of parallel steel wires spaced 2 mm apart. The grid was designed by the Bionetics Corporation (ref. 6) to count fiber intercepts. The wires in the grid were electrically connected so that voltage existed between any two adjacent wires. Fibers contacting or falling across adjacent wires provided a short circuit path and were burned out. Fiber intercepts time history data were obtained by recording the burnout pulses.

Calibration of the charged grid detector in the fiber test chamber at NASA - Langley (ref. 6) indicated a counting efficiency of 0.70 for fibers with lengths greater than 2 mm. Fibers less than 2 mm long passed through the grid without being detected.

Light Emitting Diode (LED) Detector

This device was an interrupted light beam detector developed by TRW (ref. 5) to obtain time-history fiber count data. Fibers passing through a light beam caused partial or total obscuration of the beam. The output signal from a detector upon which the beam was focused, was processed for counting the number of obscurations greater than preset levels. By relating fiber size to degree of obscuration, an indication of the number of fibers exceeding a given size (or equivalent length) passing through the beam could be obtained.

The instruments used in the outdoor fire tests at Dugway employed a light emitting diode light beam source and a silicon detector. Two models of the instrument were used. One was a wholly self-contained, battery-powered unit (fig. 12) which was developed to be attached to the Jacob's ladder for remote sensing of carbon fibers. It was limited to counting fibers with lengths greater than 4 mm. The other model was a ground-based unit which had been developed for the earlier outdoor tests at China Lake (ref. 5). The ground-based unit had a capability for counting fibers with lengths greater than 2 mm, however, because its light beam was horizontal and carbon fibers tend to float with a random orientation in a horizontal plane in the air, the counting efficiency was reduced to 0.54 for fibers with lengths greater than 2 mm in a normal spectrum of fire-released fiber lengths.

Absolute data from the LED's for the outdoor tests must be treated with discretion since the instruments counted a maximum of only 12 events in one test and averaged only five events per instrument per test. Some or all of these events could have been other forms of

light-obscuring material picked up from the ground by the intense thermal activity around the fire, or blown about by the ambient winds. LED operation prior to the first fire tests indicated an event counting frequency comparable to the subsequent frequency experienced during the fire tests. Because of these uncertainties and because corrections for the fire released fiber length spectra were large, the LED data obtained in reference 5 is not included in the subsequent section of comparable fiber sampling.

Millipore Filter Sampler

This sampler (fig. 13) was a type used by the National Institute of Occupational Safety and Health for collecting particles in the respirable size range (1 to 10 micrometers principal dimension). The sampler used a 0.8 μm pore size millipore filter connected to the inlet of a 2 litre per minute Mine Safety Appliance Company portable pump. The pump had to be turned on before the Jacob's ladder was raised prior to each fire test, and could not be turned off until after the Jacob's ladder was lowered after the completion of a fire test. The batteries that powered the pump were designed for an 8-hour duty cycle which was generally sufficient for the Dugway tests. The millipore filters were removed from the pumps after each test and shipped to NIOSH to be examined by their standard procedures for small fibers.

Petri Dish Collector

Petri dish collectors were placed on top of the 0.5 m high ground stakes which supported the nylon mesh cans in the circular ring sampling

line around the fire pool (fig. 1). The Petri dishes were fielded by TRW to collect a sample of fire-released carbon fibers which would contain a total spectrum of fiber lengths and diameters without concern for slippage through a mesh, and would be unencumbered by the adhesive from the other types of sampler. Fiber samples thus collected were examined with a scanning electron microscope to investigate fibrillation effects in small fibers (ref. 13).

Sticky Paper Sampler

Rectangular sheets of clear, adhesive coated polyester film, 8.2 by 12.7 cm by 0.1 mm thick were stapled to slightly larger sheets of heavy cardboard for use in sampling fiber deposition on the ground downwind of the fire pool. Placement was directly on the ground, face up. The sticky surface was protected by waxed paper, which was peeled back for the test, and then was reinstalled to prevent handling damage to the sample.

Sticky paper samplers were used as a backup system at many of the same downwind locations (fig. 1) as the nylon mesh can samplers, even though sticky paper is approximately one hundred times less sensitive than the nylon mesh for the turbulent outdoor environment.

Thermocouples

Nine to fifteen chromel-alumel thermocouples were used in each test fire to monitor the fire temperature in the vicinity of the composite specimens, the specimen response to the fire temperatures, and several overhead canister temperatures (ref. 4). The thermocouples used to measure the fire temperature were radiation-shielded by placement

within a vertically-oriented stainless steel tube (2.1 cm diameter by 4.8 cm long by 3.2 mm wall thickness).

Meteorological Instrumentation

Standard meteorological instruments were employed to obtain continuous recordings of horizontal wind speed and direction, vertical wind direction, air temperature and dew point from a time 3 to 4 hours preceding a test until one hour after the start of the fire. These instruments were installed on horizontal booms mounted at seven heights on one of the two upwind 60 m towers (fig. 2). Additional meteorological instrumentation was located on two 32 m towers 10 and 16 km downwind from the fire site. Pilot balloons with mobile observing stations were used at three locations to provide supplemental winds aloft information.

Photographic Instrumentation

Photogrammetric techniques were used to calculate the plume location, plume dimensions, and plume rise time. Ten 35 mm cameras with remotely-controlled, 5 frames per second operation were located up to 1800 m from the fire site to provide complete coverage of each test. Frame time reference signals were included in each photograph. General documentation of each test was provided by two video tape and one 16 mm color motion picture cameras, supplemented by a roving still photographs.

TEST OPERATIONS

Five outdoor aviation jet fuel pool fire tests were conducted in October and November, 1979 at the U.S. Army Dugway Proving Ground, Utah (ref. 4). Three tests (designated D-1, D-2, D-3) were conducted under meteorological conditions which controlled, within limits, the bending of the resultant fire plume and the direction of travel of the released carbon fiber. Two tests (designated S-1 and S-2) were conducted under calm meteorological conditions, which resulted in the fire plume rising almost vertically. Table II is a summary of the operational parameters for the five tests. The wind speed and direction are averages of the recorded meteorological data from the 8 m height for the duration of the fire. The design wind direction was 320° into the wind. The JP-4 aviation jet fuel was pumped into the 10.7 m diameter fire pool, forming a fuel layer 12.7 cm deep which floated on top of an 8-cm deep layer of water.

A minimum of 45 kg of carbon-fiber-epoxy composite materials were positioned on a structural steel stand over the fire. The composite material was composed of T300 carbon fibers and 5208 epoxy matrix. This material had been fabricated into a variety of aircraft structural components as a part of the NASA Aircraft Energy Efficiency (ACEE) Composite Primary Aircraft Structures program by three commercial airframe manufacturers. These composite components were made available to be burned after the companies had completed their planned manufacturing and structural testing. In addition, the U.S. Air Force provided three composite speedbrakes and part of a composite empennage

which had been removed from fighter aircraft after receiving operational damage. Detailed dimensions and masses of these components are given in Appendix L of ref. 4.

Test D-1

This first of three dissemination tests was conducted with 16 carbon fiber composite components uniformly distributed on the surface of the support stand 2.5 m above the surface of the pool. The 8.5 m diameter stand was centered in the 10.7 m diameter pool. Meteorological conditions combined with the thermal energy released by the fire resulted in a fire plume which was tilted approximately 67° from vertical, and horizontally averaged 40° to the west of the design downwind direction. Much of the fire at the pool was blown under the downwind side of the specimen support stand and many of the composite components were only slightly burned, primarily by radiation from the flames.

Test D-2

This test was conducted with 23 carbon fiber composite components distributed on the surface of the support stand 2.5 m above the surface of the pool. Based on the observed behavior of the fire in test D-1, the composite components were concentrated on the downwind side of the support stand with only a few scattered around the upwind region. The combined meteorological and thermal conditions produced a fire plume which was tilted approximately 64° from vertical, and horizontally averaged 31° to the east of the design downwind direction.

Figures 14 and 15 are photographs of the fire and plume which are characteristic of the dissemination fires. The effect of the wind in sweeping much of the fire under the downwind side of the specimen support is readily apparent in figure 14. A few of these specimens that were mounted vertically on the support stand can be seen. Also, the pulsating nature of the combustion process is evident in the plume as it moves away from the fire. A longer portion of the downwind plume is shown in figure 15, and a sudden break in the thermal rise can be seen in the plume before it passed through the Jacob's ladder sampling net which extended essentially vertically below the two balloons.

Test D-3

The third dissemination test was conducted with only four composite components, each of which were larger than most of the other components used in the fire tests. These were the left and right horizontal stabilizers from an F-16 which had crashed, and two composite structural surface panels from another F-16 vertical stabilizer. The specimen support stand was displaced downwind and the four components were grouped together in much the same position as installed on an aircraft.

Combined meteorological and thermal conditions on test D-3 produced a fire plume which was tilted approximately 62° from the vertical, and horizontally averaged 6° to the west of the design downwind direction. At about seven minutes into the burn, thermal weakening caused the specimen support stand to collapse, lowering the composite components from 2.5 m to 0.8 m above the surface of the pool.

Test S-1

The first source test was conducted with eleven carbon fiber composite components uniformly distributed over the surface of a new support stand, 2.1 m above the surface of the pool, which was built to replace the collapsed stand from test D-3. The extremely light wind velocity allowed the thermal energy to loft the fire plume almost vertically (fig. 16) through the center of the overhead canopy. The old, collapsed specimen support stand can be seen in the right background. The new support stand is almost totally engulfed within the fire. Also evident in this photograph is the necking down of the fire plume to a diameter of only about 0.40 of the pool diameter at a height of 3.5 m (0.32 times the pool diameter). The total plume rise to the atmospheric inversion layer at about 700 m and the subsequent drift downwind can be seen in figure 17 which is a photograph taken from a helicopter about 20 minutes into the burn.

S-2

Test S-2 was the last of the outdoor aviation jet fuel fire tests and was conducted with twenty-two composite components to be burned. Twenty of these were distributed uniformly over the surface of the support stand 2.1 m above the surface of the pool. The remaining two were flat plates positioned on an auxiliary stand 0.5 m above the pool. Extremely light and variable winds again allowed the thermal energy to loft the fire plume almost vertically through the overhead canopy. The atmosphere inversion layer did not appear to be quite as sharply defined as for test S-1, but the S-2 plume stabilized at a height of about 600 m.

RESULTS AND DISCUSSION

The principal results of the five large-scale fire tests conducted at Dugway Proving Ground are presented in the following sections. The major emphasis is placed on quantifying the release of single carbon fibers as they offer the greatest possibility of causing damage to electronic equipment in the dissemination area downwind from burning composite structural components.

Single Fiber Source Strength

The number of single carbon fibers that were released by the aviation jet fuel fire burning composite components in each of the outdoor tests was determined by several independent fire plume sampling systems (Table III). The results shown in Table III are classed as estimates for several reasons. The fire plume did not always completely pass through the sampling system; thus engineering judgement based on eyewitness observation and photographic documentation determined the position of the plume that was within a given sampling system. The estimates in Table III are based on the total plume and assume that the portion outside the sampling system had the same fiber density as the portion within. Even when the plume did pass completely within, the ratio of the sampled area to the plume total cross-sectional area was very small, varying from $1/2300$ to $1/5,800,000$. Only fibers with lengths greater than 1 mm were considered in the determination of the number released. Fibers shorter than 1 mm were known to exist (ref. 13), but were not considered significant in causing damage to electronic equipment (ref. 3). Small fiber characterization is discussed in a later section.

The source strength estimates (ref. 4) for the canister collectors in the overhead canopy (Table III) are believed to be reliable values. For the two source tests they are the only values, and the plume was fully contained within the sampling canopy. For the dissemination tests, D-2 and D-3, the source strength estimates are considered acceptable when corrected for the 60 to 80 percent of the plume that missed the canopy.

Vertical array source strength estimates (Table III) were also made (ref. 4) and are believed to be low by a significant amount as discussed in the next section, even though they had the highest ratio of sampled area to total plume area, 1:2325. Field calibration in ambient temperature dry air showed the sampling efficiency was low, 0.54, indicating poor adhesion. Carbon fiber sampling data reduced from tests in the Naval Surface Weapons Center Shock Tube in the same time period (ref. 12) have shown that other types of sticky samplers had their dry efficiency reduced to less than ten percent in fire tests which was attributed to the high levels of soot and water vapor that resulted from the jet fuel fire. The outdoor fire plumes contained high levels of soot (figs. 14 and 16) and would be expected to have high levels of water vapor in the portion of the plume close to the fire. Thus, a significant reduction in sampling efficiency would be expected in the fire plume at the vertical array. Another indication of reduced sampling efficiency was apparent from the fiber deposition on those stainless steel mesh cans that were mounted alongside the overhead canister collectors in the source tests (ref. 4). The mesh can data averaged only about ten percent of the fiber deposition in the canisters.

Source strength estimates from nylon mesh cans located 0.5 m above ground on the sampling lines downwind from the fire site are believed to be reliable but could be in error due to the low ratio of sampled area to total plume area, 1:5,800,000. This source strength estimate was based on the observation that the fire-released fiber source is initially lofted to a stabilized height in a plume which has Gaussian distributions in both vertical and horizontal directions. As the plume is carried downwind, the fiber cloud continues to expand primarily due to atmospheric turbulence and meandering of the wind. Reflections of the fiber paths from the ground surface and from the atmospheric inversion layer eventually result in an essentially uniform distribution of fibers vertically between the ground and the inversion height. This vertical uniformity is assumed to be established in a downwind distance equal to three inversion heights plus the initial distance from the fire site to the stabilized cloud height.

The four ground-supported sampling lines farthest downwind were at distances greater than the criterion for vertical fiber uniformity, and the data from the mesh can samplers along these lines was taken to be representative of the portion of the fiber cloud passing directly over them up to heights between 500 and 600 m.

Jacob's ladder source strength estimates (Table III) were made from the nylon mesh vu-graph data (ref. 5) and are believed to be low by a factor of between two and three based on comparisons with fiber deposition data from several other types of sampler instrumentation that were also installed on the Jacob's ladder net. The ratio of the vu-graph sampled area to the total plume area was 1:12,200.

Comparative sampling.- The size of the Jacob's ladder sampling net and the lifting capability of the balloons made possible the installation of numerous fiber sampling instruments in addition to the 420 nylon mesh vu-graph samplers (fig. 10). The carbon fiber vertical-plane deposition profiles for dissemination test D-3 are shown in Figure 18(a) through (j) at several altitudes from 238 m to 64 m. Between these altitudes the net was approximately 200 m downwind from the fire even though the base of the net was anchored to the ground 117 m downwind (ref. 5).

The deposition profiles are based on fiber counts from each of the several types of instruments used. The raw data counts for the nylon mesh vu-graphs (ref. 14) were reviewed for evidence of bias by any of the six people who did the counting. None was found.

The nylon mesh can samplers were installed adjacent to the nylon mesh vu-graphs at a number of locations (fig. 10) in order to obtain comparative data. Upon removal at the end of test D-3, approximately half of the mesh cans were counted by Dugway and the results are labeled as nylon mesh can samplers, initial count (fig. 18). The remainder of the mesh cans from the Jacob's ladder were sent to NASA for to obtain an alternate count and investigation along with the cardboard canister collectors. Results of this analysis are shown as nylon mesh can samplers, alternate count (fig. 18). As the result of an apparent bias in the data from the alternate count, at the higher values of deposition, the nylon mesh can samplers were returned to Dugway, counted, and these results are shown as a check count in figure 18. The charged-grid detector data (fig. 18(i)) was previously reported (ref. 6), but has subsequently been corrected to include all fibers with lengths greater than 1 mm.

Straight lines have been drawn between data points for each sampling system shown in the various parts of figure 18 in order to aid in making a numerical comparison of the different measurements. The ratios of the fiber deposition on the indicated sampling system to the deposition on the nylon mesh vu-graphs were found to be:

Nylon mesh can sampler, initial count	2.5:1
Nylon mesh can sampler, check count	2.8:1
Canister collectors	3 :1
Charged grid detectors	2.7:1

Another comparison of sampling instrumentation was made (fig. 19) for the near-ground-level vertical deposition in the three dissemination tests measured by the bottom row of vu-graphs on the Jacob's ladder and nylon mesh cans on one of the nearby ground-based sampling lines. The vu-graphs were located 125 m downwind from the fire and at 3 m altitude; the mesh cans were 208 m downwind and at 0.5 m altitude. The fiber depositions can not be compared directly, but an adjustment can be made to the sampled values to place them at a common location. The adjustment was based on the variation in peak deposition with distance downwind from the fire site as shown in figure 20 based on the mesh can sampling lines. In addition the bottom row of vu-graphs on the Jacob's ladder were oriented more nearly horizontal than vertical at 62 to 70 degrees from the vertical due to the distorted catenary shape of the supporting net. This inclination would be expected to change the aerodynamics of flow through the nylon mesh and therefore affect the fiber deposition. With these uncertainties, the nylon mesh can samplers indicated an adjusted deposition that was from 1.1 to 1.3 times the deposition on the nylon mesh vu-graphs on the bottom row of the Jacob's ladder.

Therefore, it appears that for carbon fiber deposition in a vertical plane, the source strength determined by from the nylon vu-graphs (Table III) should be increased by a factor of 2.5 to 3.0. This discrepancy may have been caused by an aerodynamic blockage from the wide supporting frame of the vu-graph, or it may have been the result of a lower efficiency adhesive sprayed on the nylon mesh. Calibration of the vu-graph sampler in a wind tunnel comparable to the mesh can calibration has never been performed, so either of these factors could account for the apparent reduced sampling effectiveness of the vu-graph. Using an average adjustment factor of 2.75, the source strength estimates for the three dissemination tests determined from the Jacob's ladder samplers would become 8.5, 9.6, and 6.6×10^8 fibers for tests D-1, D-2, and D-3, respectively. Using these same values of source strength for the vertical array would imply that sampling efficiency of 0.095, 0.118, and 0.090 respectively for tests D-1, D-2, and D-3 for the silicone-grease-coated stainless steel mesh cans in the humid soot filled jet fuel fire plume.

The mass of single fibers released in each of the five outdoor fire tests (Table IV) was determined from the source strength and mean fiber length for each of several sampling systems. Although the numbers of fibers were different as determined from the field measurements on the vertical array and the Jacob's ladder (refs. 4 and 5, respectively), the calculations for the mass released resulted in essentially the same values. The most likely value of mass released (Table IV) in the dissemination tests was calculated using the source strength numbers of fibers for the Jacob's ladder increased by the adjustment factor of 2.75 to account for sampling effectiveness. The maximum likely value of mass released by this adjusted calculation was 0.60 percent of the initial

carbon fiber mass in test D-2, well below the assumed value of one percent used in the risk assessment (ref. 3).

Fiber release rate.- An almost uniform rate of carbon fiber release (fig. 21) during burning of the composite components was measured by the charged grid detectors on the Jacob's ladder (ref. 6). The cumulative history of the release in the three dissemination tests indicated an essentially linear release with time for tests D-1 and D-2 until the last several minutes of burning when the release rate decreased to essentially zero as the fire burned out. The initial delay in sensing fibers was the time required for fibers to be released from the matrix and be transported to the charged grid. The difference in the indicated rate of release for these two tests was caused primarily by the deliberate concentration of most of the composite components on the downwind side of the support stand in test D-2 compared to the uniform distribution of specimens in D-1. Sixty-six percent of the available composite material was either consumed or released in test D-2 compared to 44 percent in D-1 (ref. 4).

The cumulative history of released fibers in test D-3 was also essentially linear until the specimen support stand collapsed after about eight minutes of burning. A lower rate of release continued for the duration of the fire apparently due to the lower placement of the composite material in the fire. If the stand had not collapsed and the composite material had responded in the same fashion as in tests D-1 and D-2 with a linear release of fibers throughout the duration of the fire, the projected total deposition would have been 2.5 times the observed

deposition. The source strength of single fibers for test D-3 would have been 1.7×10^9 fibers which would be 1.7 times the D-2 source strength; or about the same proportions as the masses of initially available composite material in the two tests.

Comparative fiber size spectra.- The spectra of lengths of carbon fibers released in outdoor aviation jet fuel fire tests are shown in figure 22. The shaded regions indicate the range of results from two earlier tests at the Naval Weapons Center (ref. 2) and from the fire Dugway Proving Ground tests. Only those fibers with lengths greater than 1 mm were of interest in the study to assess electrical risk. The preponderance of fire-released fibers were between 1 and 3 mm long, and the mean lengths were between 2.5 and 3.5 mm for these seven tests.

A comparison of mean length determinations from the various sampling systems is given in Table V for the five Dugway tests. Most of the systems provided fibers with consistent mean lengths. One notable exception appeared to be the vertical array of stainless steel mesh cans which collected fiber lengths with mean values generally between 4 and 5 mm. This could have been the result of a low altitude lofting of longer-than-normal fibers which then did not remain airborne for a sufficient time to reach the Jacob's ladder or the longer-range downwind sampling lines. The variation in mean fiber length with height on the Jacob's ladder (fig. 23) indicates no particular trend with releases between 2.5 and 3.7 mm for data from the nylon mesh vu-graph samplers (ref. 5) which were substituted by nylon mesh cans and can collected (Table V). A more probable cause for the indicated longer mean lengths on the vertical array could be associated with a bias in slippage of shorter

length fibers that might be expected with the apparent poor collection efficiency of the stainless steel mesh with silicone grease in the heavy soot and water vapor environment.

One other anomaly was the mean fiber length of 4.9 mm on the downwind ground sampling line Bravo, 19,110 m from the fire site. All other ground samplers from this distance back to the Jacob's ladder had mean fiber lengths between 2.9 and 3.7 mm. Detailed review of the length distribution of the fibers on sampling line Bravo indicated a disproportionate quantity in the 7-8 mm and in the 9-12 mm length intervals compared with any other sampling line distributions. Further investigation showed that sampling line Bravo was in close proximity to the sites of a number of previous carbon fiber tests that had been conducted at Dugway. One of these (ref. 15) had deposited approximately 33 kg of chopped virgin carbon fiber (nominal 6 and 12 mm lengths) on two relatively small areas four years earlier. Visual observation showed that an indeterminate amount of this material was still on site, in and around vegetation on the ground. Re-suspension of carbon fibers from this ground deposit continued to occur three years after the initial deposit, but at greatly reduced numbers of fibers and generally at greatly reduced fiber lengths. However, after a deliberate man-made disturbance, both the number and mean length of re-suspended fibers increased dramatically. Thus the anomaly of mean length on sampling line Bravo could have been the result of traffic on the ground just prior to or during the time that the nylon mesh can samplers were in place.

The spectra of diameters for carbon fibers greater than 1 mm in length released in the outdoor aviation jet fuel fire tests (fig. 24) indicated that many of the fibers had been reduced in diameter. Mean

diameters ranged from 3.6 to 5.3 μm from determinations in various samplers from the seven tests (refs. 2 and 4). This diameter reduction from the nominal 7 μm diameter virgin fiber suggested that oxidation in the high temperature portion of the fire was the probable cause. Substantial fiber oxidation in fires had been predicted on the basis of laboratory thermogravimetric analysis coupled with fire plume dynamics and chemistry studies (ref. 1).

The possible health considerations of fibers which were smaller than those of electrical concern led to the installation of ten millipore filter samplers on the Jacob's ladder (fig. 10) for each of the three dissemination tests. The filters were shipped to the Robert A. Taft Laboratories of the National Institute for Occupational Safety and Health (NIOSH), Cincinnati, Ohio after each test. The following indented section has been extracted from two letter reports on their findings.

The samples were analyzed utilizing phase contrast optical microscopy at a magnification of 400X. All fibers (any particle with an aspect ratio greater than 3:1) were recorded (Table VI) and sized by both diameter and length with 100 microscope counting fields observed on each sample. A sample collection time of 20 minutes (nominal average burn time for each test) was used in the determination of concentrations even though the total sample collection time varied between 6 and 7 hours. By using only the burn time it was assumed that all fibers collected were the result of the burning of carbon composites and that extraneous airborne ambient

fiber exposures were zero. A flow rate of 1.7 litres per minute was used in determining the air volume to account for a reduction in flow rate from the initial 2.0 litres per minute since the burning of composites usually occurred 6 to 7 hours after the sampling instrumentation had been turned on.

The results (Table VI) indicated that the greatest number of fibers found in any filter area counted was four which related to a fiber concentration of approximately 1.4×10^5 fibers per cubic metre (0.14 fiber/cc). A few of the samples were so contaminated with particulate material that fiber determinations were not feasible. From the 24 samples that could be counted, a total of 26 fibers were found. Classification of these by length and diameter (Table VII) indicated that all fibers were larger than 5 μm and less than 3.5 μm in diameter. Fifteen of the samples underwent further particulate characterization utilizing transmission electron microscopy. Samples were examined at a magnification of 10,000X utilizing selected area electron diffraction and energy dispersive X-ray analysis for particulate identification.

All fibers were identified as being carbon and having rugged surface features with irregular shaped ends. Other non-fibrous particulates were found in a size range from less than 1.0 μm to 5.0 μm in diameter; most of these smaller particulates were identified as being carbon with some of the larger ones having an elemental composition of aluminum,

iron, and silicon. No attempt was made to quantitate a fiber exposure from these results because of the small number of fibers observed.

The location of the small fibers counted by NIOSH on the Jacob's ladder sampling net for test D-3 (fig. 25) is compared to the portion of the net within which the nylon mesh vu-graphs had defined fiber depositions greater than 100 fibers/m^2 for fibers with lengths greater than 1 mm. The small fibers appear to have been near the periphery of the large-fiber cloud or completely outside of it. Similar effects were observed in tests D-1 and D-2. An approximate estimate of the source strength of the small fibers was made using the average of one fiber counted per millipore sample (total of 26 fiber in 24 samples) which corresponded to an average concentration of $4 \times 10^4 \text{ fibers/m}^3$. This average concentration moved past the Jacob's ladder at a velocity of 5.3 m/s for the 20 minute burn time, which would produce an average deposition of $2.5 \times 10^8 \text{ fiber/m}^2$ in the vertical plane of the net. If the size of the small-fiber cloud was defined by the area of the Jacob's ladder bounded by the millipore filter samplers, it would be approximately 130 m high by 240 m wide. The total number of small fibers in the average of the three fire plumes would then be 7.8×10^{12} fibers, which is approximately 10^4 more than the source strength of fibers greater than 1 mm in length.

Sussholz in his study of micron-size carbon fibers (ref. 13) concluded that small fibers (diameter less than $3 \mu\text{m}$ and lengths less than $80 \mu\text{m}$) occurred with an estimated frequency of 100 times the

occurrence of fibers greater than 1 mm in length for two cases of large, outdoor aviation jet fuel fire tests at the Naval Weapons Center. The principal source of these small fibers was a fibrillation phenomena. Evaluation of the carbon fibers collected in the Petri dishes during the three Dugway dissemination fire tests provided evidence (ref. 13) that the fibrillation phenomena could be attributed to oxidation effects on a parent single carbon fiber causing it to split into multiple fibrils as its overall diameter was reduced.

Single Fiber Downwind Deposition

The footprint of single fiber deposition downwind from the fire site to 19.1 km is shown in figure 26 for the three dissemination fire tests. The extent of these footprints was established by two or more fibers deposited on the vertical surface nylon mesh can samplers (ref. 4). Local shifts in wind direction were indicated by the kinks and bends that occurred in the footprint as the fiber cloud was transported downwind. In general, the decrease in wind velocity that occurred in test D-2 and D-3 relative to D-1 resulted in more lateral or crosswind dispersion and a wider footprint. Although a Gaussian crosswind distribution would be expected on the average given a large number of tests, the individual test distributions consisted of several discrete peaks with no detectable deposition between peaks on the three or four farthest downwind sampling lines.

Clump Strength

Clumps of carbon fibers were released from the burning composite material in a similar manner to the single fibers. The clumps were

lofted and carried downwind by the fire plume but, because of their much higher fall rate, not to as great a distance as the single fibers. Estimates of the source strength of fiber clumps (Table VIII) indicate a reasonable consistency between the three sampling systems data. Most of the clumps (up to 75 percent) contained from 2 to 10 fibers within the clump. Significantly greater numbers of clumps were released from the dissemination tests than from the source tests, indicative of the influence of the atmospheric wind velocity in breaking the clumps loose from the composite residue. The total mass of the fiber clumps was approximately the same as the most likely value of the mass of the single fibers with lengths greater than 1 mm. Clumps were not disseminated as far downwind as single fibers. Their principal threat to electronic equipment might be expected to occur from the potential for release and resuspension of single fibers from the clumps after deposition on the ground downwind from the fire site. However, as indicated previously (ref. 15) the number of fibers likely to be resuspended decrease dramatically within a short time.

Strip Deposition

Strips of carbon-fiber-epoxy composite material were delaminated from the surfaces of the composite structural components of the intense thermal activity within the aviation jet fuel pool fires. Many of these strips were delaminated before much of the epoxy matrix had been consumed in the fire. The strips were lofted in the fire plume and carried downwind from the fire site varying distances depending on their size, shape and mass. Typical of this downwind deposition were the two

strips of composite (fig. 27) deposited on one of the nylon mesh vu-graphs on the Jacob's ladder in test D-3.

After each test, personnel searched the ground area near the fire site and along the downwind path of the plume and recovered most of the composite strip material. All strips within designated grid areas were picked up, placed in plastic bags, and subsequently weighed. Several bags judged to be representative of the strip material were counted in addition to being weighed in order to establish an approximate number of strips per gram of recovered mass. Table IX presents a summary of all of the composite strips recovered in the search area out to 100 m from the fire site. Footprints of the ground deposition of the composite strips (fig. 28) clearly show a pattern of rapidly decreasing deposition mass density with increasing range downwind. The footprints of strip deposition for the two source tests (fig. 28(d) and (e)) are more nearly symmetrical around the fire pool indicative of the light and variable wind conditions.

Mass Balance and Oxidation

Debris from each of the seven outdoor, aviation jet fuel fire tests (five at Dugway and two at Naval Weapons Center) was gathered, sampled, weighed and summed to account for as much of the mass of the initial composite structural components as possible (table X and fig. 29). Between 15 and 60 percent of the original mass remained in place after the fire; between 1 and 29 percent were recovered in the downwind sweep as strips and pieces. Fiber clumps and single fibers each accounted for less than one percent of the original mass. This left between

40 and 80 percent of the original mass not specifically accounted for, or unrecovered. Up to 30 percent of the original composite mass was epoxy matrix and most of this material was consumed in the fire. Thus, at least 10 percent and perhaps as much as 50 percent of the original mass was unrecovered carbon fiber. A substantial portion of the unrecovered carbon fiber was undoubtedly consumed by oxidation in the fire in the same manner as the epoxy matrix, but at a slower rate. Certainly the diameter reductions for fire-released fibers greater than 1 mm in length (fig. 24) and the characteristics of the fibrillated small fibers (ref. 13, and Table VII) are conclusive evidence that oxidation of the released fibers occurred, and most of the oxidation had to occur while the fiber was a part of the composite mass on the support stand. In addition, substantial fiber oxidation in fires had been predicted on the basis of laboratory thermogravimetric analysis coupled with fire plume dynamics and density studies (ref. 1).

Characteristics of Burned Composite Residue

A significant quantity of carbon-fiber composite material remained in place on the support stand after 20 minutes of burning within or near the flames of the 10.7 m pool fires. The debris in figure 30 is the residue from the F-16 stabilizer that was burned in test D-3. The four pieces retained identifiable shapes in spite of major delaminations, oxidation of most matrix resin, and release of fibers. In the foreground are a large number of strips as described earlier. The expanded wire mesh on which the man is standing was the

specimen stand that had supported the stabilizer 2.5 m above the ground, but had collapsed during the fire. Forty-two percent of the mass of the two vertical stabilizer skins remained on the stand. When it was picked up and placed in plastic bags to be weighed, most of it lost its physical integrity and became a large quantity of ribbons and strips of essentially single-ply composite with only a slight amount of matrix char holding fibers together.

In contrast, the two horizontal stabilizers retained 64 and 78 percent respectively of their composite skins. The apparent difference was the presence of the aluminum honeycomb core which conducted heat away from the surface on which the flames impinged, and maintained a greater degree of physical integrity. The adhesive bonding the aluminum ribbons together within the core as well as the adhesive bonding the composite skins to the core had been destroyed by the high temperatures, but the core did not melt and the combination of rivets and cross-ply of laminate kept the structure together. In order to determine the residual mass of the horizontal stabilizer skins, the composite had to be separated from the metal by taking apart the composite portion one ply at a time by hand.

The speedbrake components burned in tests D-1, S-1, and S-2 also were aluminum honeycomb construction and displayed similar characteristics of retaining much of their physical integrity. The principal mechanism by which composite material was disseminated appeared to be a gradual erosion from the edges of the structure. Forty-five, 51 and 61 percent of the composite material remained in the speedbrakes in these three tests.

Flat composite laminates and composite stiffened flat panels were almost completely destroyed when they were directly in the fire. Heavier sections of composite retained some physical integrity but lost most of their matrix. In the dissemination tests the wind blew the flames to one side of the pool and specimens on the upwind side of the support stand, only a few metres away from the flames, received little damage and generally less than ten percent mass loss.

Two sets of four plates, each 30 cm square, by 6 and 8 mm thick respectively were included in the composite specimens burned in test S-2. All plates were cross-ply laminates. All were severely burned and delaminated, but retained their shape. No effects of initial thickness could be observed. Four of the plates were mounted horizontally and four vertically. The four vertical plates lost an average of 52 percent of their mass, whereas the horizontal plates lost an average of only 44 percent probably because one surface was supported on the steel expanded wire mesh. On top of the support stand, 2.1 m above the fire pool surface, plates at the center of the fire lost 46 percent of their mass, and near the periphery of the flames plates lost 60 percent probably from an increased local velocity due to entrainment of air. Two plates near the center were located on an auxiliary stand, 0.5 m above the surface of the pool. They lost an average of 37 percent of their mass compared with the 46 percent at 2.1 m height.

Temperatures measured during each fire (figs. 31-35) varied considerably with time and location. The pulsating or fluctuating nature of the fire produced large transients in thermocouple data.

In an effort to average out some of the short-time transients, the temperature shown were taken as two-minute averages of the raw data (ref. 4). The influence of the radiant heating on the composite specimens can be seen from the upwind thermocouples in figures 31 and 32. The higher temperatures measured in the flames generally also produced higher specimen temperatures on the downwind side. Temperatures in the flames and in the stabilizer (fig. 33) do not show any obvious indication of the support stand collapsing after seven minutes of burning, even though the specimen came to rest 0.5 m above the surface of the fire pool. Therefore, the change in release rate (fig. 21) must have been due to a local velocity change and not due to the temperatures of the fire. No explanation has been found for the large differences in thermal characteristics of the two nearly identical source tests (figs. 34 and 35). Peak temperatures were nearly the same but there was a much greater variation in temperature in different parts of the fire in test S-2 than in S-1.

Temperature averages for the total burn time for each thermocouple are shown in figure 36. These clearly show the large variations in temperature that occur with respect to location within the fire and within specimens in or near the flames. The higher temperatures measured in these fires ranging from 1100 to 1400 K agree quite well with measured values reported in the analysis of fire tests (ref. 16) which were performed to assist in model development for fire characteristics.

Overall average temperatures measured by all of the thermocouples in each test (fig. 37) indicate comparable thermal conditions in the three dissemination tests, but again indicate a marked difference in the

two source tests which remains unexplained. In all cases, temperatures were high enough to destroy carbon fiber-epoxy composite specimens and loft the released fibers, clumps and strips away from the fire site.

CONCLUDING REMARKS

A realistic release of carbon fibers from burning composites has been demonstrated in a series of five large-scale outdoor aviation jet fuel fire tests. These tests were conducted at the U.S. Army Dugway Proving Ground, Utah to validate the source strength of single fibers used in the assessment of risk for electronic equipment failure. The magnitude of the fiber release was quantified by several independent assessments with instrumentation developed and fielded by Dugway, TRW, Inc., the Bionetics Corporation, and NASA. The results previously reported by Dugway and TRW for source strength based on their principal fire plume sampling systems were judged to be too low because of deficiencies in the samplers. Comparisons with other sampling systems have established a multiplying adjustment factor of 2.75 for the fibers counted on nylon mesh vu-graphs and 10 for fibers counted on the silicone-grease-coated stainless steel mesh can samplers.

The most likely values for the source strengths range from 6.6 to 9.6×10^8 fibers for the dissemination tests, and from 2.2 to 2.9×10^8 fibers for the source tests. These are equivalent to a mass of single fibers released ranging from 0.2 to 0.6 percent of the initial mass of carbon fiber in the composite material. These percentages for release were well below the assumed value of one percent used in the NASA risk assessment.

Mean fiber lengths for fibers greater than 1 mm in length ranged from 2.5 to 3.5 mm for these tests. Mean diameters for samples of these same fibers ranged from 3.6 to 5.3 μm which was indicative of significant oxidation occurring in the composite material within the fire.

Downwind dissemination footprints for the fire-released fibers were measured as far away as 19.1 km. Fiber cloud strengths based on these far-field dissemination depositions also provided a reasonable estimate of the source strength.

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TABLE I.- CARBON FIBER SAMPLING INSTRUMENTATION USED FOR OUTDOOR
AVIATION JET FUEL FIRE TESTS.

Tower supported:

Stainless steel canister collector	61	
Stainless steel mesh can sampler	221	
		<hr/> 282

Balloon-supported Jacob's ladder:

Nylon mesh can sampler	95	
Nylon mesh vu-graph sampler	420	
Cardboard canister collector	30	
Charged grid detector	8	
Light emitting diode (LED) detector	2	
Millipore filter sampler	10	
		<hr/> 565

Ground supported, 91 m - 19 110 m downwind:

Nylon mesh can sampler	833	
Sticky paper sampler	464	
Light emitting diode (LED) detector	2	
Petri dish	40	
		<hr/> 1339

TABLE II.- SUMMARY OF OPERATIONAL PARAMETERS FOR
OUTDOOR FIRE TESTS

Operational parameter	Test number				
	D-1	D-2	D-3	S-1	S-2
JP-4 fuel used, litres	11368	11386	11371	11368	11386
Burn time, minutes	18.9	20.4	22.9	28.4	25.4
Composite mass, kg					
Initial	46.20	45.48	70.77	48.58	45.55
Residual	25.98	15.35	36.78	15.89	26.72
Wind speed, m/s	6.4	5.8	5.3	0.7	1.1
Wind direction, °	360	289	326	variable	variable
Stability category	Neutral	Neutral	Neutral	Stable	Stable

TABLE III.- ESTIMATES OF SOURCE STRENGTH FOR SINGLE CARBON FIBERS WITH
LENGTHS >1 mm

Sampling system	Test				
	D-1	D-2	D-3	S-1	S-2
Canister collectors in overhead canopy	-	11.1×10^8	3.9×10^8	2.9×10^8	2.2×10^8
Stainless steel mesh cans in vertical array	1.5×10^8	2.1×10^8	1.1×10^8	-	-
Nylon mesh vu-graphs on Jacob's ladder net	3.1×10^8	3.5×10^8	2.4×10^8	-	-
Nylon mesh cans 0.5m above ground, downwind	8.9×10^8	6.3×10^8	2.0×10^8		

TABLE IV.- ESTIMATES OF SINGLE FIBER MASS RELEASED IN OUTDOOR FIRE TESTS

Sampling system	Mass released in test*, percent of initial carbon fiber mass				
	D-1	D-2	D-3	S-1	S-2
Overhead canisters**	-	0.98	0.19	0.2	0.2
Vertical array (ref. 4)	0.2	0.2	0.1		
Jacob's ladder (ref. 5)	0.20	0.22	0.10		
Most likely value***	0.55	0.60	0.28	0.2	0.2

*Mass released was calculated as estimated number of fibers times average length time initial cross-sectional area times fiber density.

**On tests D-2 and D-3, the sampling array intersected less than one third of the smoke cloud.

***Most likely value of mass released was calculated using adjusted source strength numbers of fibers for the Jacob's ladder as discussed in the comparative sampling section of text, or the overhead canister values for the source tests.

TABLE V.- AVERAGE FIBER LENGTHS DETERMINED FROM VARIOUS SAMPLING SYSTEMS AT
VARIOUS LOCATIONS, mm

Sampling system	Location	Test numbers				
		D-1	D-2	D-3	S-1	S-1
Canister collector	Overhead	2.6	3.1	2.7	3.3	3.2
Stainless steel mesh can	Vertical array,					
	overall	5.0	4.4	5.2		
	@ 1.5m	4.2	4.8	3.7		
	@ 53m	3.7	3.2	2.8		
Nylon mesh vu-graph	Jacob's ladder	3.2	3.1	3.2		
Nylon mesh can	Jacob's ladder			3.4		
Cardboard canister collector	Jacob's ladder			2.8		
Nylon mesh can	Downwind @ 0.5m altitude					
	Line AA, 116m		4.3			
	BB, 208 m	4.5		3.3		
	DD			2.9		
	FF			3.0		
	Zulu			3.7		
	X-Ray			3.4		
	Victory			3.5		
	Papa			3.0		
	Bravo			4.9		

TABLE VI.- NIOSH-OBSERVED SMALL CARBON FIBERS COLLECTED IN MILLIPORE FILTERS
ON JACOBS LADDER FOR THREE DISSEMINATION FIRE TESTS

Filter location on Jacob's ladder	Total fibers counted from 100 microscope fields			Concentration, fibers/m ³		
	D-1	D-2	D-3	D-1	D-2	D-3
H6 V3	0	0	1	0	0	4x10 ⁴
H6 V11	1	2	0	4x10 ⁴	7x10 ⁴	0
H6 V19	0	0	3	0	0	11x10 ⁴
H10 V3	3	*	3	11x10 ⁴	*	11x10 ⁴
H10 V8	4	*	0	14x10 ⁴	*	0
H10 V14	1	0	0	4x10 ⁴	0	0
H10 V19	*	0	2	*	0	7x10 ⁴
H14 V3	1	*	2	4x10 ⁴	*	7x10 ⁴
H14 V11	2	0	*	7x10 ⁴	0	*
H14 V19	*	0	1	*	0	4x10 ⁴

*Too many particulates, unable to observe fibers

TABLE VII.- SIZE DISTRIBUTION OF SMALL FIBERS COLLECTED IN MILLIPORE FILTERS
DURING THREE DISSEMINATION FIRE TESTS

Fiber length, μm	Fiber diameter, μm				Percent of total fibers in each length category
	<1.2	1.7	2.5	3.5	
5.0	4	6	-	-	38
6.5	1	7	2	-	38
9.5	-	2	1	-	12
13.5	-	-	-	2	8
19.0	-	-	-	-	-
27.0	-	-	-	1	4
Percent of total fibers in each diameter category	19	58	12	12	

Note: Fibers were sized at 400X magnification. Placement of fibers in each of the size categories does not necessarily represent the actual size, but only the nearest fit.

TABLE VIII.- ESTIMATES OF SOURCE STRENGTH FOR CARBON FIBER CLUMPS

Sampling system	Number of clumps released in test, millions				
	D-1	D-2	D-3	S-1	S-2
Canister collectors on overhead	-	19	14	2	7
Stainless steel mesh cans on vertical array	34	88	16		
Nylon mesh vu-graphs on Jacob's ladder net	15	14	18		

TABLE IX.- CARBON-FIBER-EPOXY COMPOSITE STRIPS LOFTED IN FIRE PLUME AND
DEPOSITED ON GROUND DOWNWIND IN DUGWAY PROVING GROUND FIRE
TESTS

Test No.	Approximate number of strips	Mass of strips recovered, g			Recovered mass, % of initial composite mass
		Inside towers	Beyond towers	Total	
D-1	8500	1120	291	1411	3.1
D-2	24200	3154	846	4000	8.8
D-3	4600	231	532	763	1.1
S-1	5400	479	405	884	1.8
S-2	6200	498	528	1026	2.3

TABLE X.- MASS BALANCE FOR COMPOSITE MATERIALS BURNED IN LARGE-SCALE OUTDOOR
AVIATION JET FUEL FIRE TESTS

Composite material mass	Test						
	Dugway Proving Ground					Naval Weapons Center	
	S-1	S-2	D-1	D-2	D-3	11	13
Initial, kg	48.58	45.55	46.20	45.48	70.77	3.77	22.52
Residual, support stand, kg	15.89	26.72	25.98	15.35	36.78	1.09	4.00
downwind sweep, kg	0.88	1.03	1.41	4.00	0.76	1.09	0.54
clumps, kg	0.18	0.46	0.16	0.15	0.14	-	-
single fibers, kg	0.08	0.05	0.18	0.20	0.14	-	-
total, kg	17.03	28.26	27.73	19.70	37.82	2.18	4.54
Unrecovered material, kg	31.55	17.29	18.47	25.78	32.95	1.59	17.98
percent of initial	65	38	40	57	47	42	80

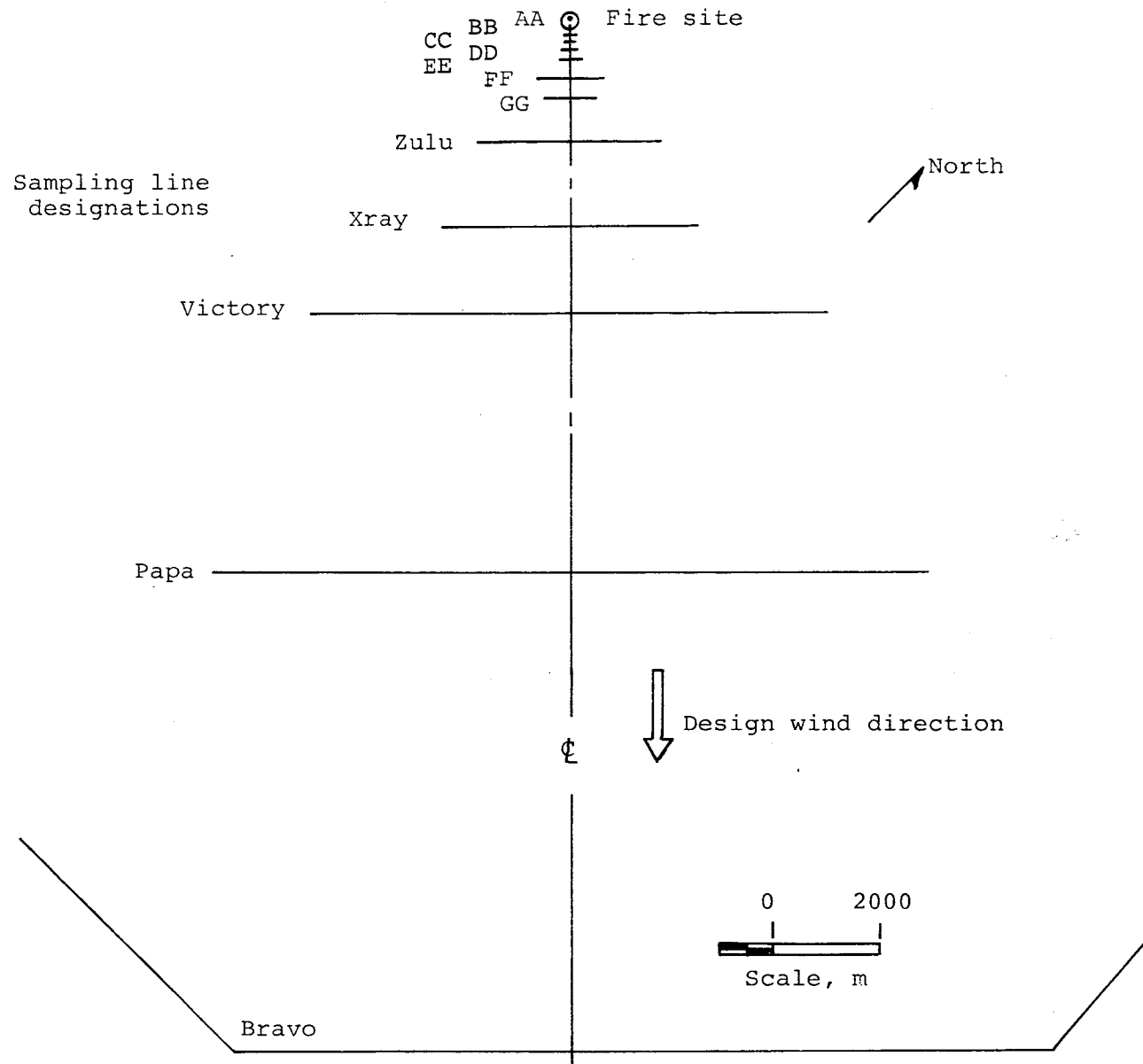


Figure 1.- Ground-based sampling lines located downwind from the fire site.

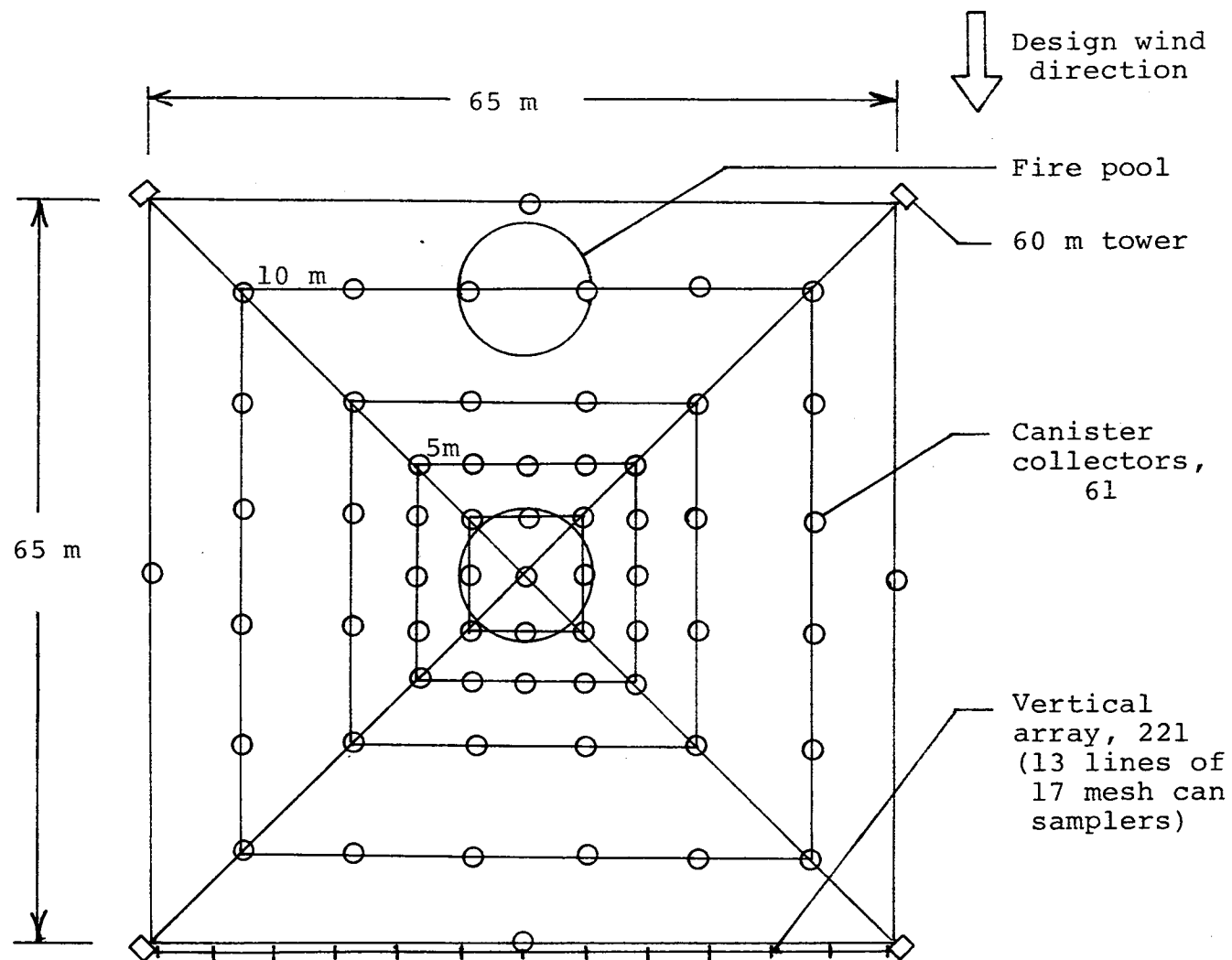


Figure 2.- Tower-supported overhead canopy and vertical array for fire plume sampling at the fire pool site.



Figure 3.- Overhead canopy of canister collectors suspended from towers.

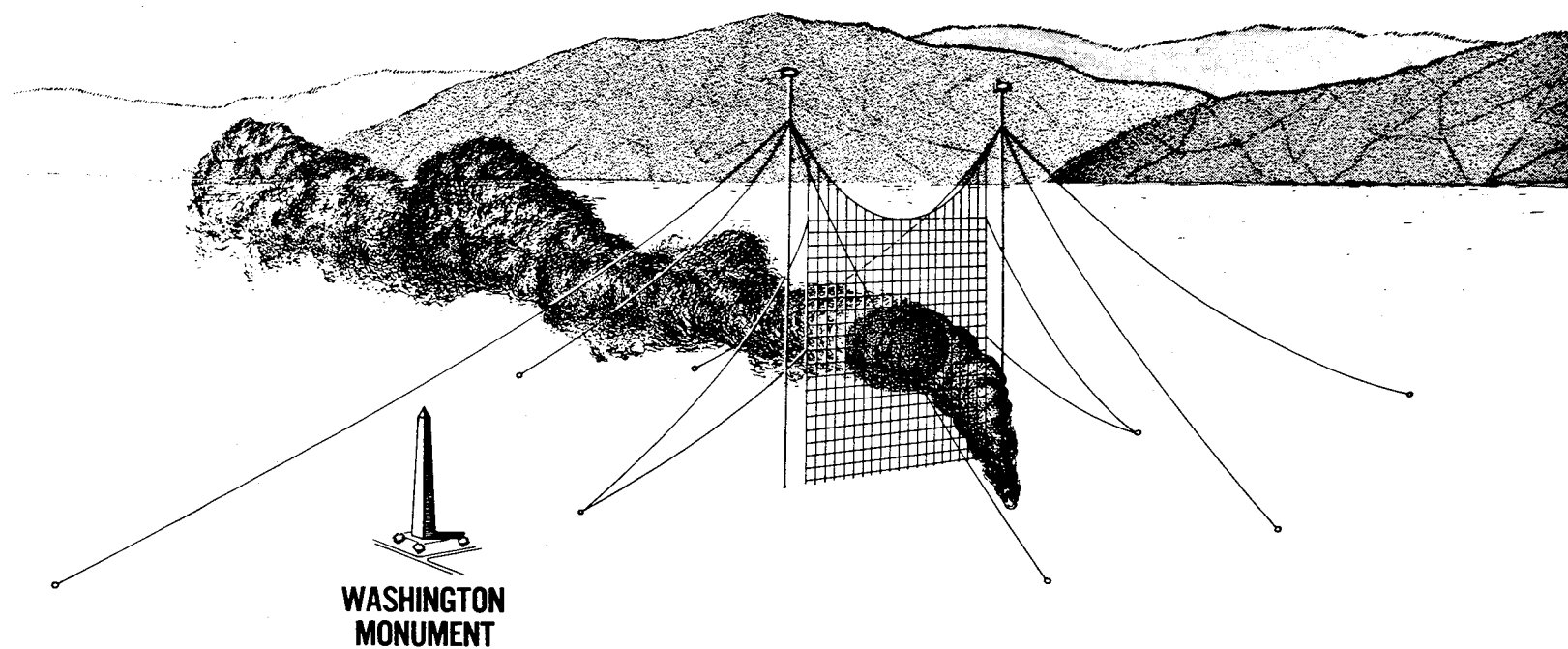


Figure 4.- Balloon-supported Jacob's ladder fire-plume sampling net.

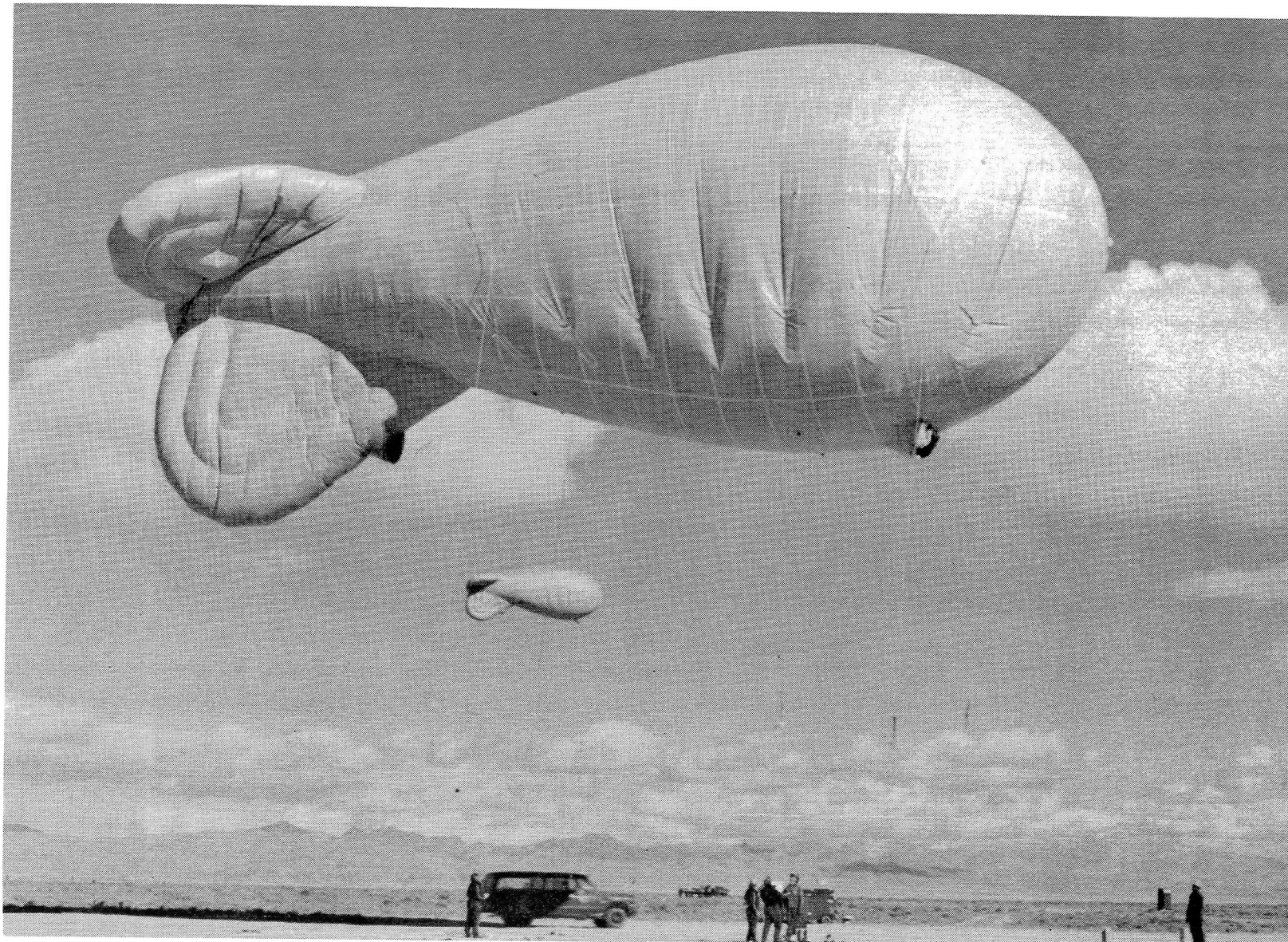


Figure 5.- Air Force Geophysics Laboratory balloons at beginning of Jacob's ladder erection.

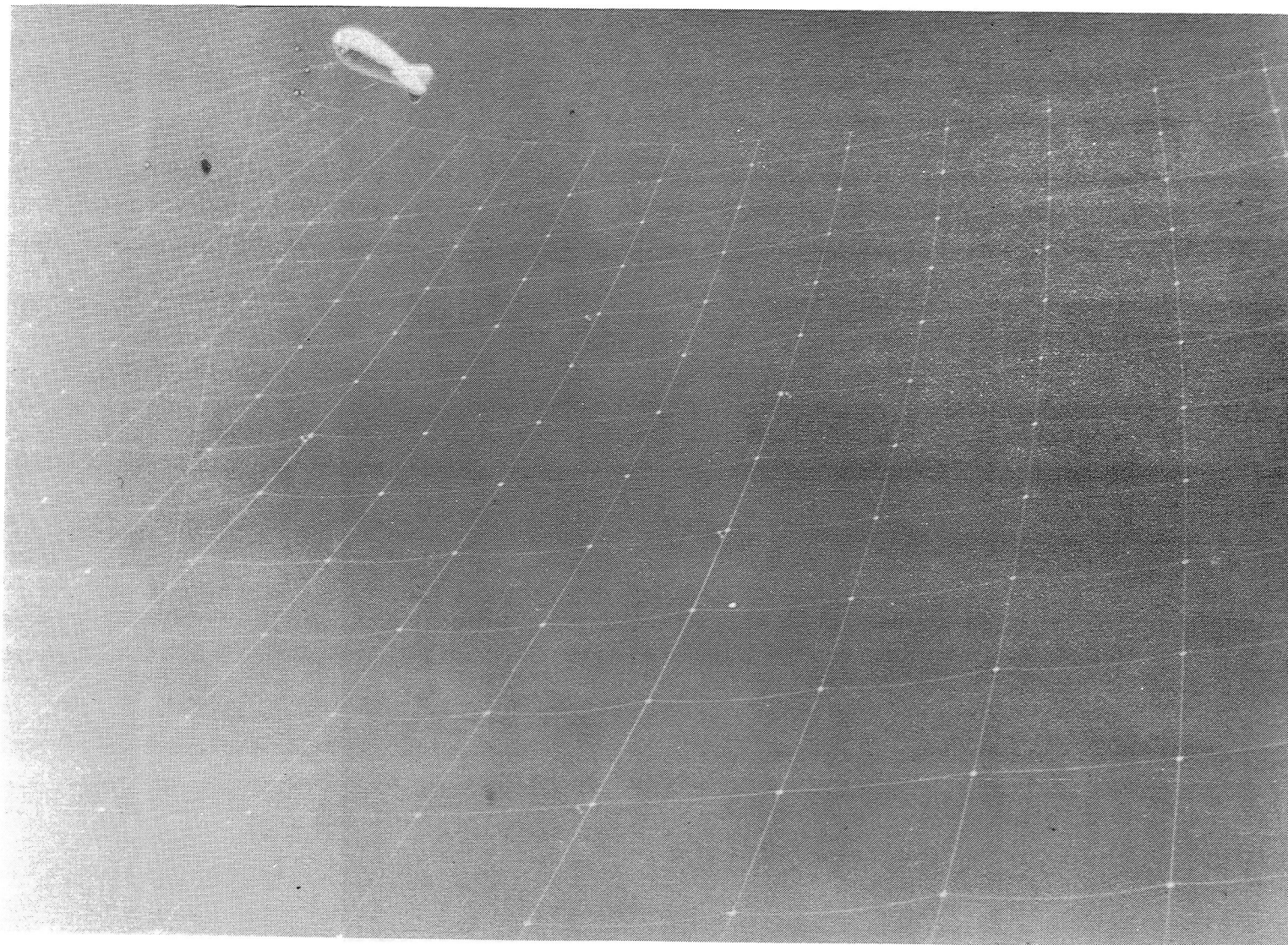


Figure 6.- One quadrant of balloon-supported Jacob's ladder sampling net.

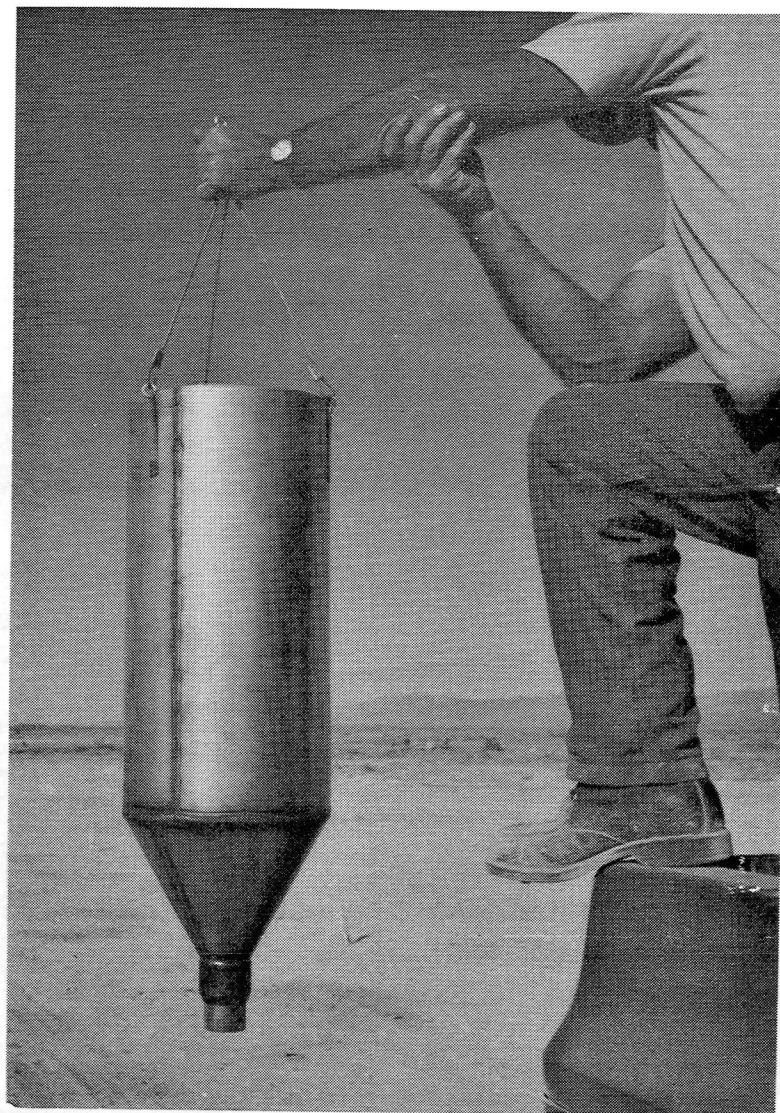


Figure 7.- Stainless steel canister collector for fiber sampling from overhead canopy.

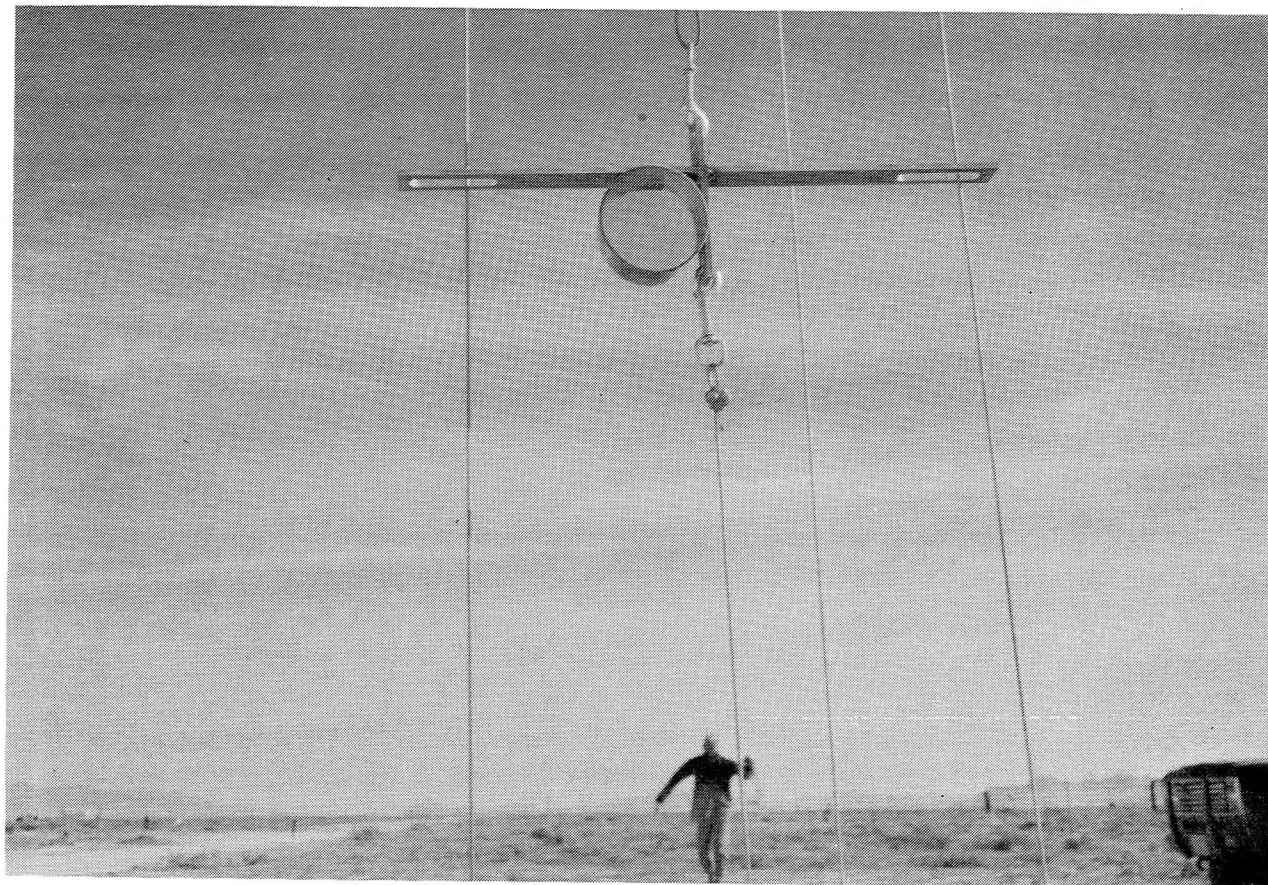


Figure 8.- Stainless steel mesh can sampler on vertical array.

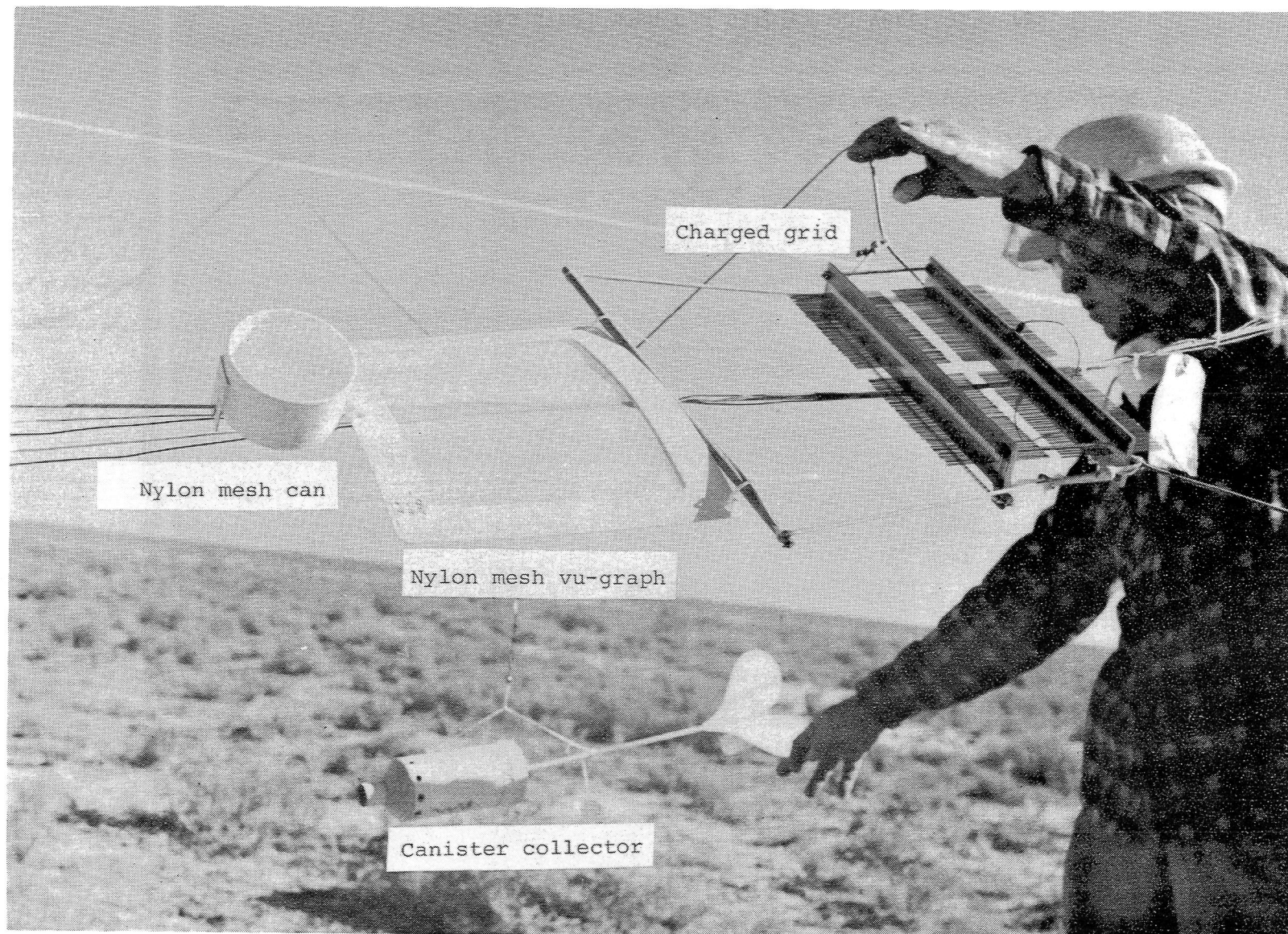


Figure 9.- Four fiber detector/collector instruments at one location on Jacob's ladder.

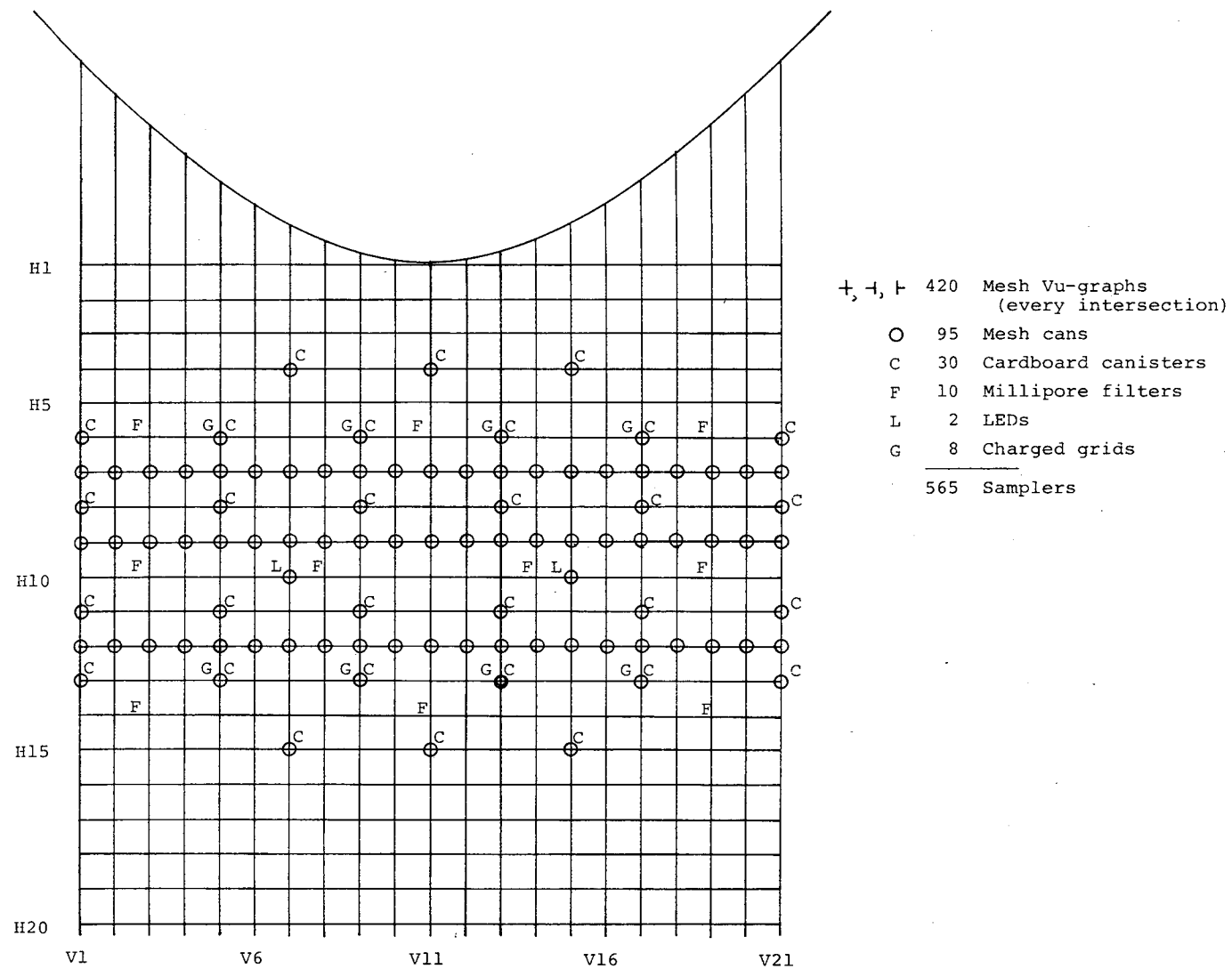


Figure 10.- Instrumentation location on Jacob's ladder fire plume sampling net.

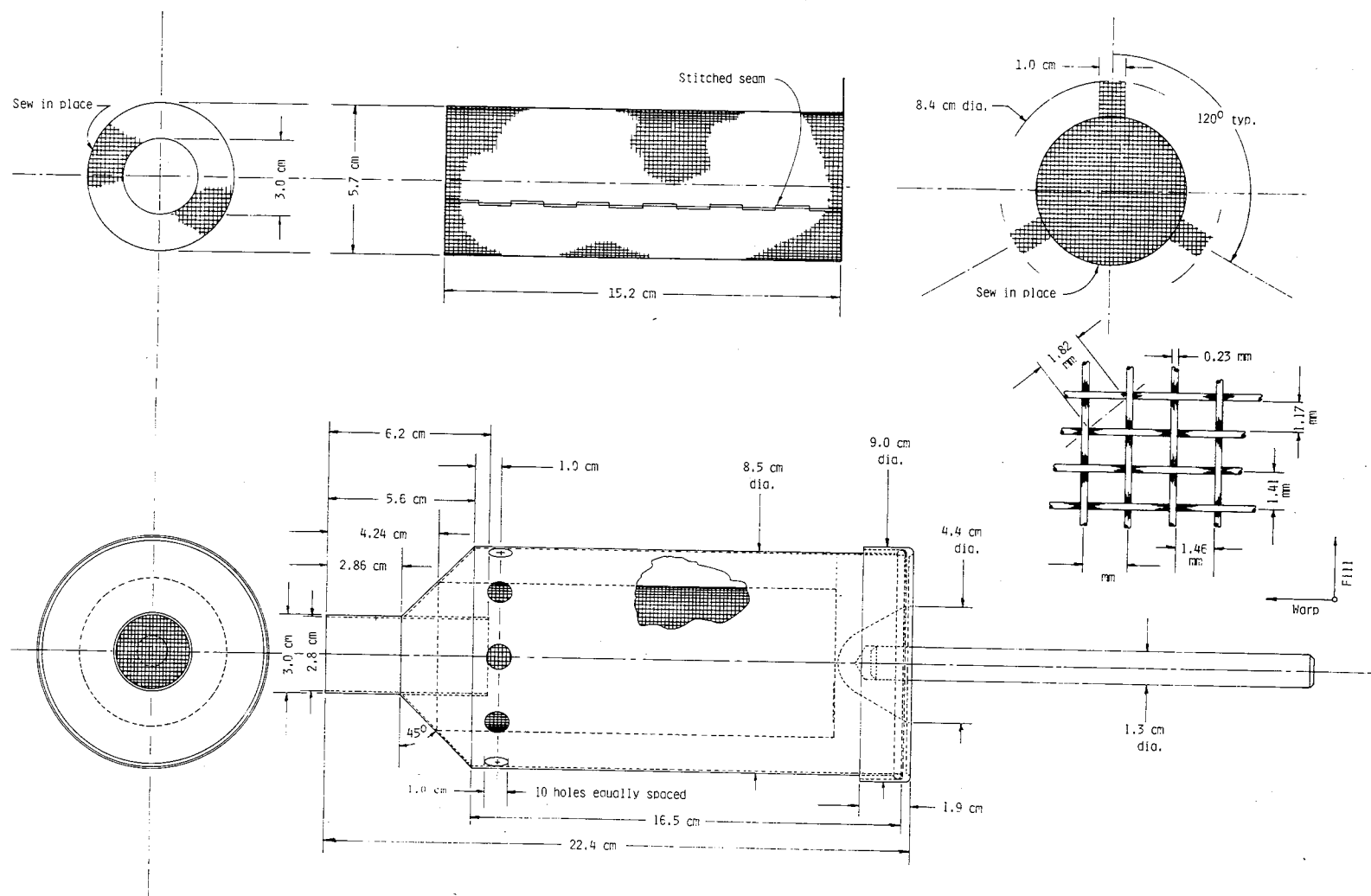


Figure 11.- Cardboard canister collector for fiber sampling from Jacob's ladder.

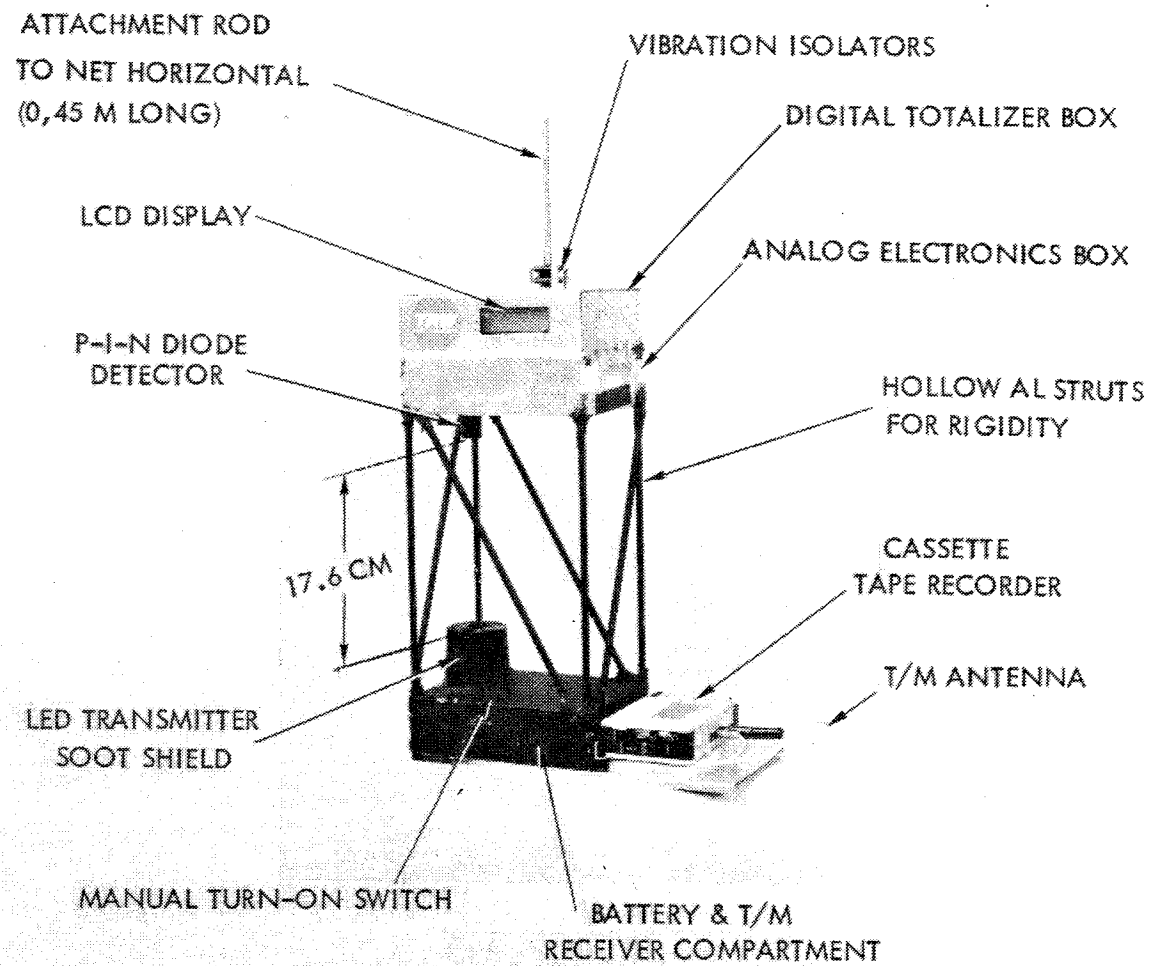


Figure 12.- Self-contained, battery-powered Light Emitting Diode Detector (LED) developed for remote sensing of carbon fibers.

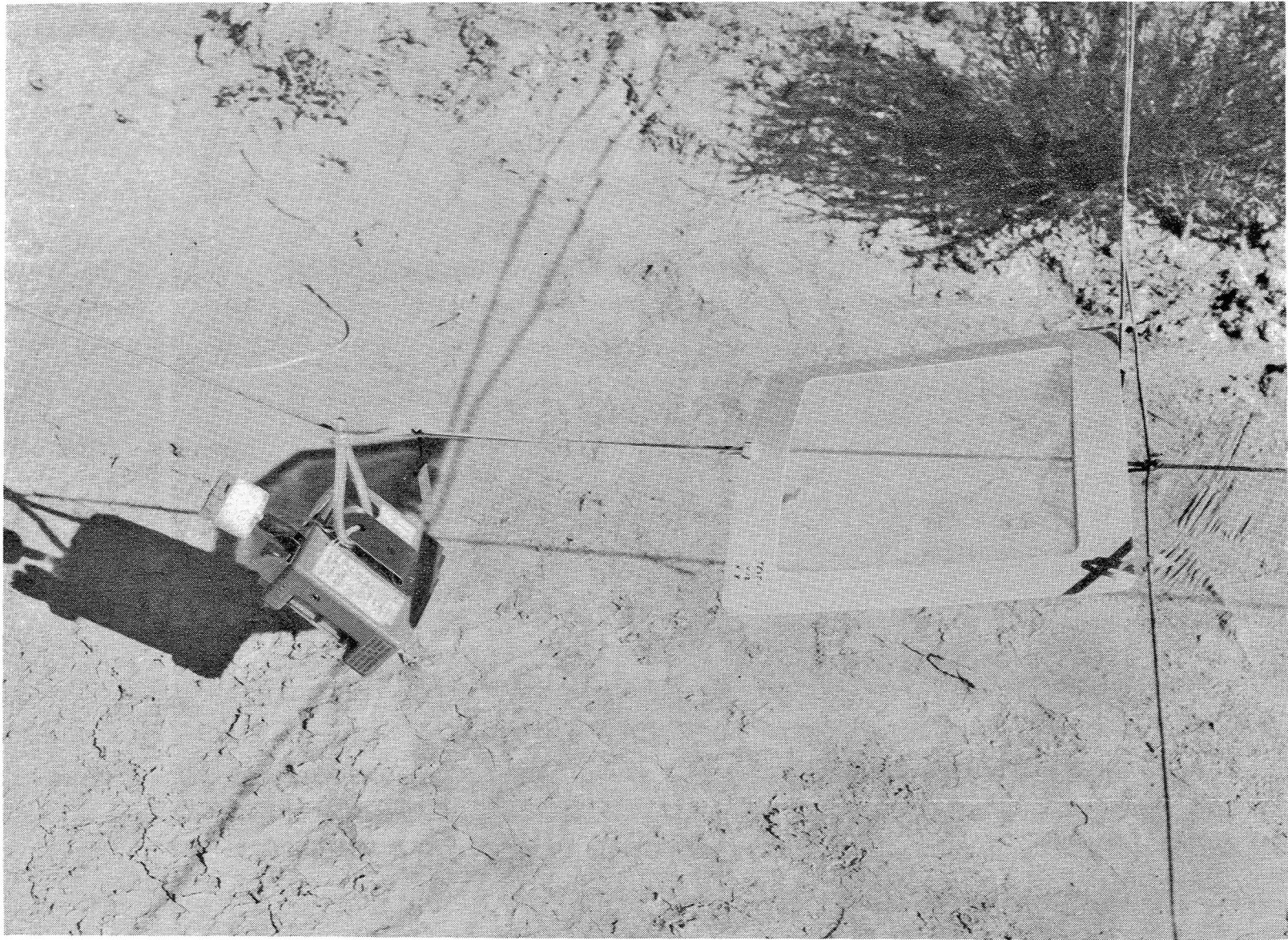


Figure 13.- Millipore filter sampler suspended from Jacob's ladder.

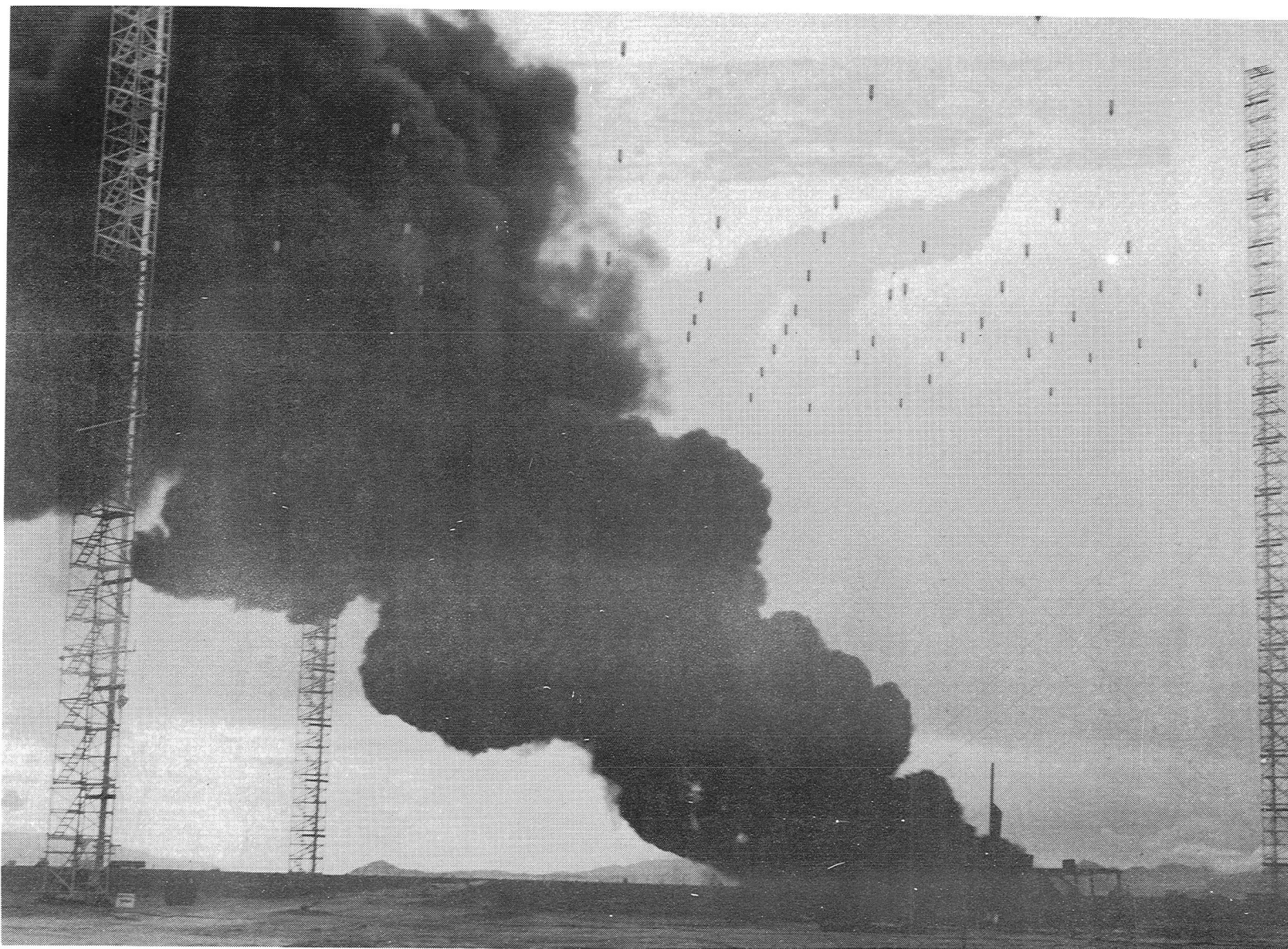


Figure 14.- Dissemination fire and initial part of smoke plume in region of towers, test D-2.

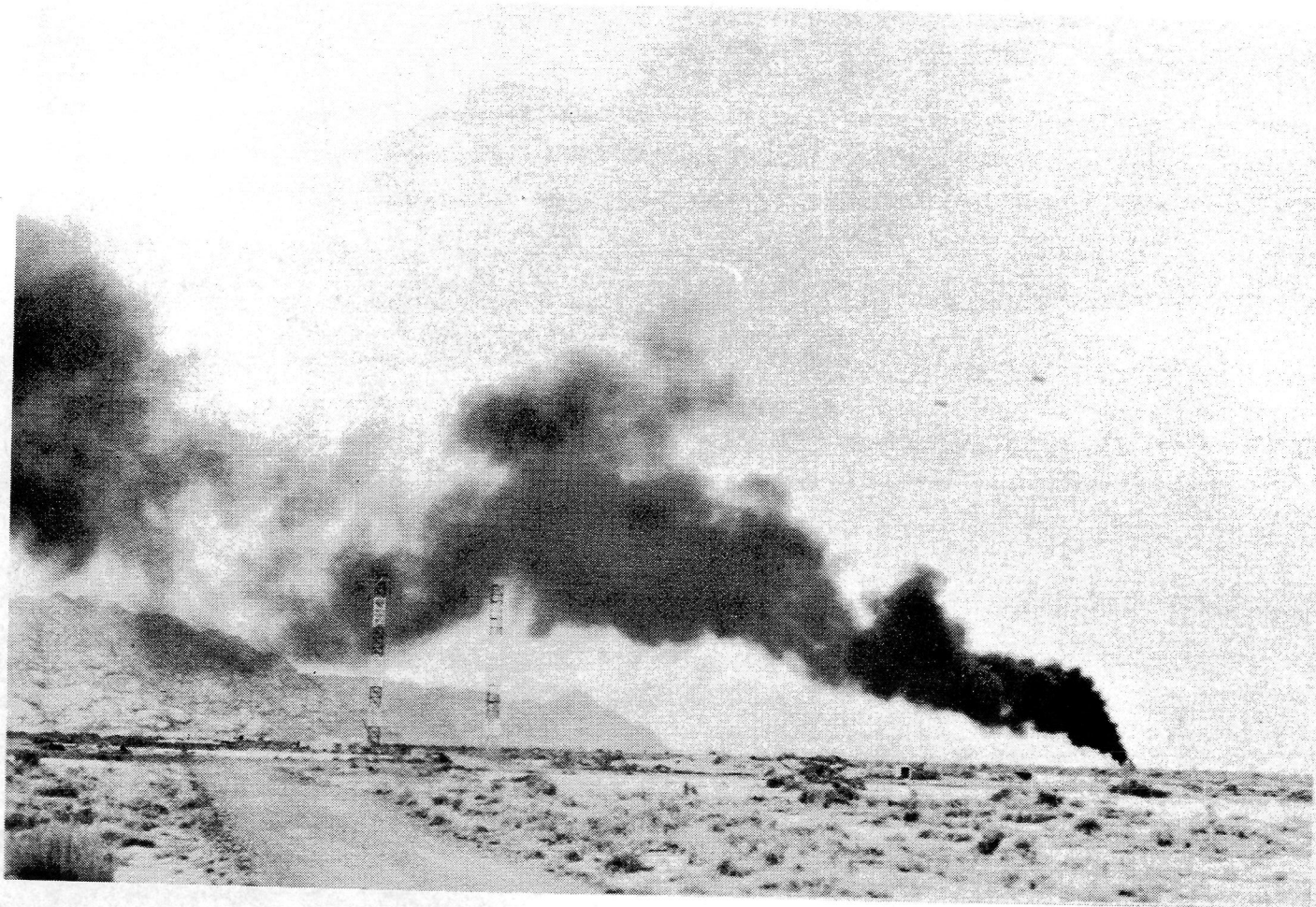


Figure 15.- Dissemination fire, balloons, and two km length of plume, test D-2.

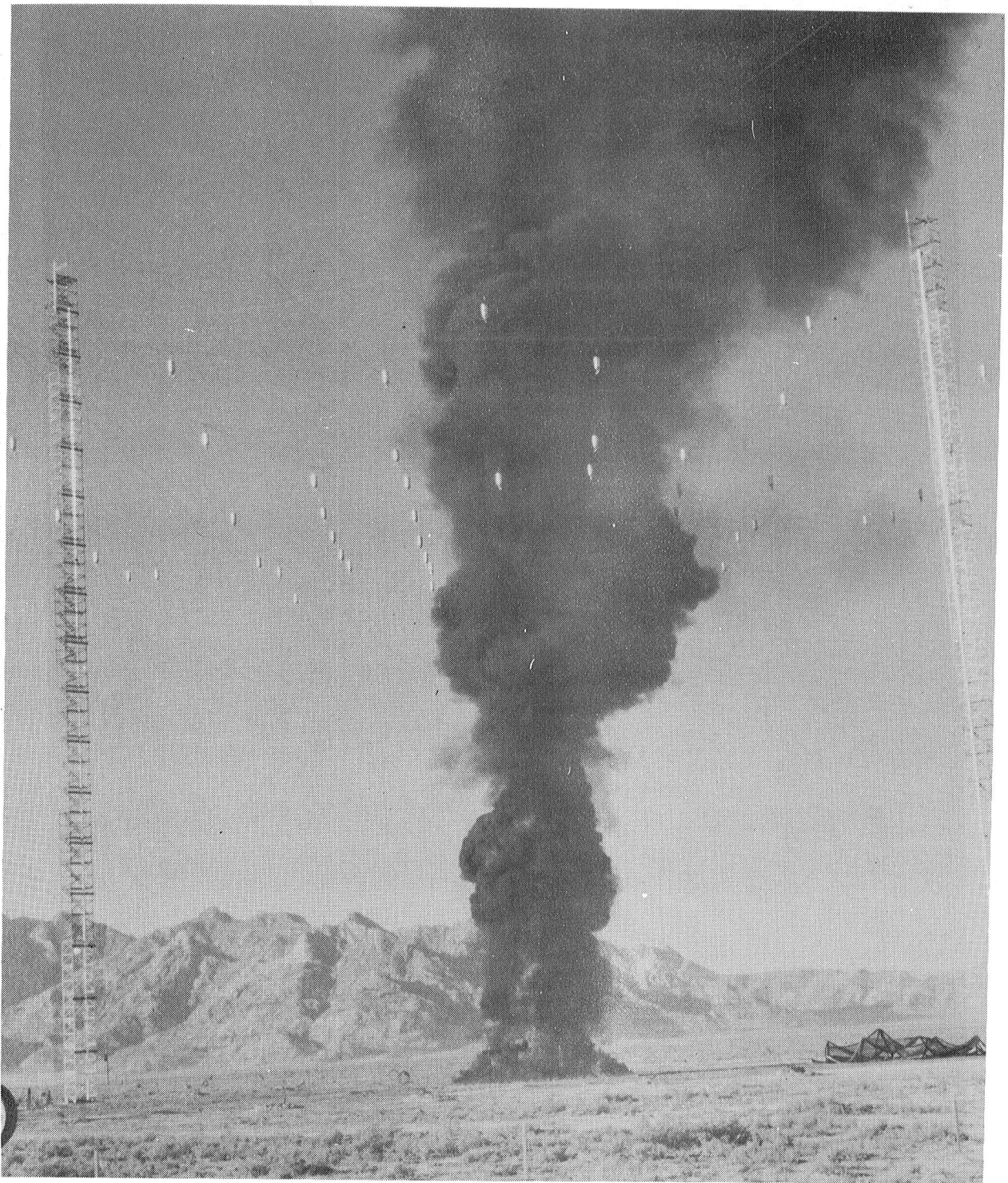


Figure 16.- Source fire and smoke plume rising vertically through overhead canopy of canister collectors, test S-1.

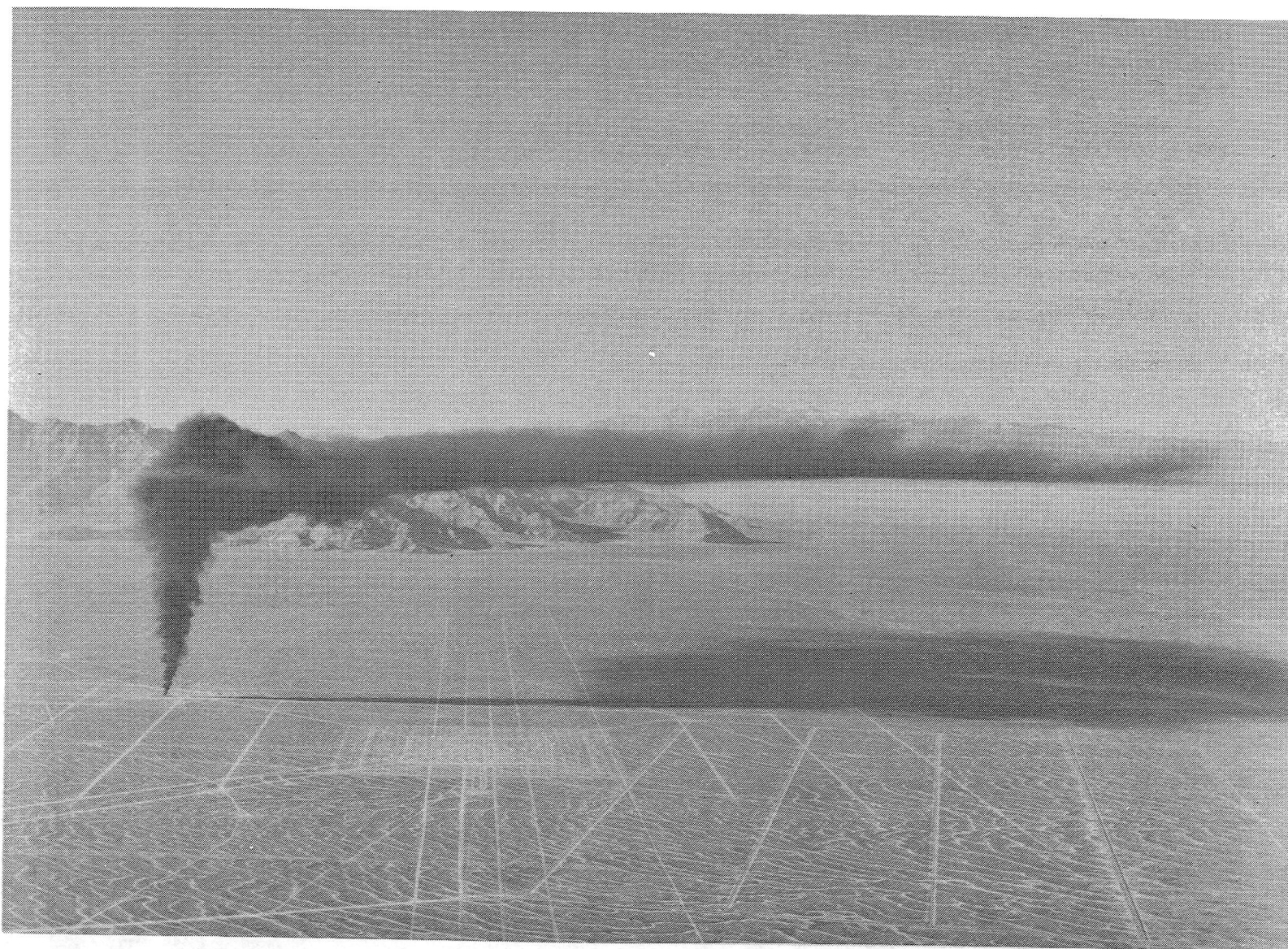


Figure 17.- Source fire and smoke plume movement below inversion layer, test S-1.

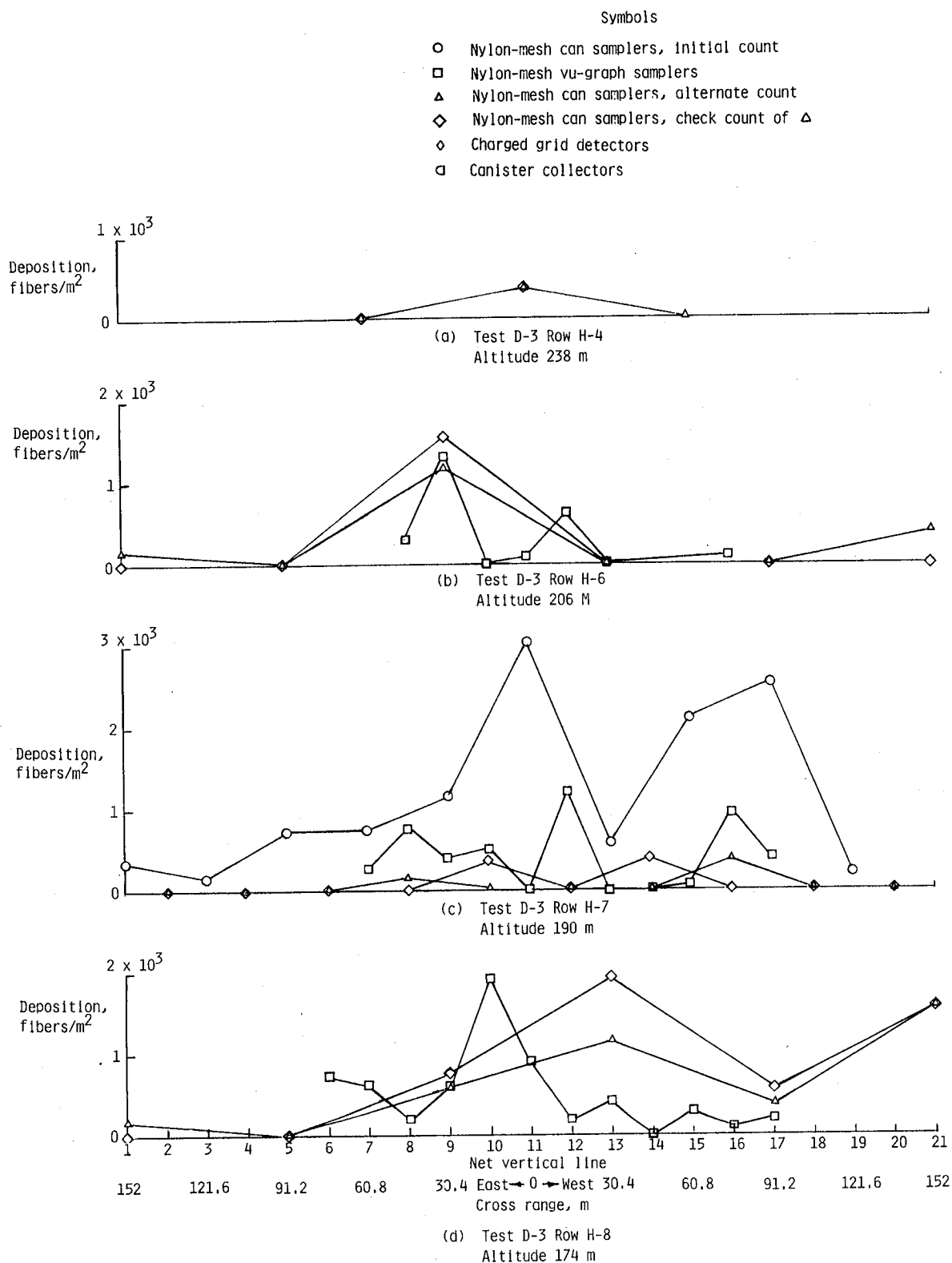


Figure 18.- Crossrange carbon-fiber deposition profiles.

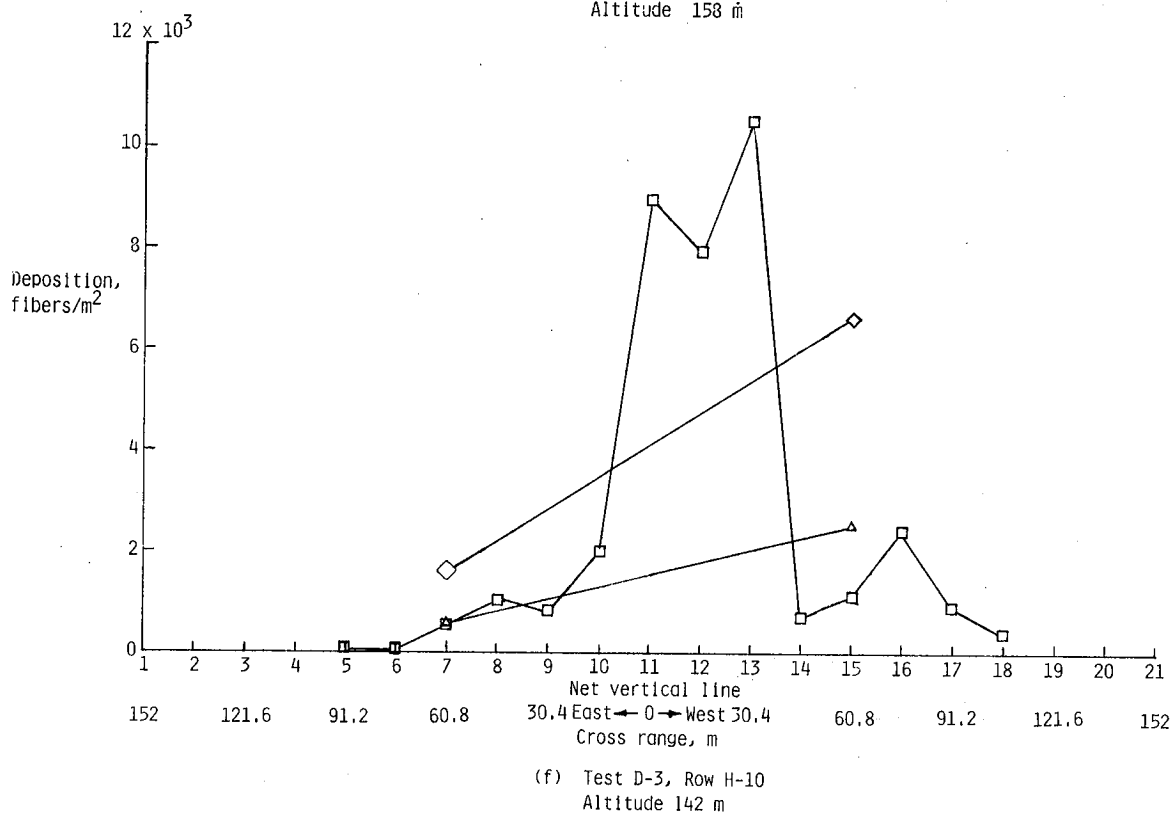
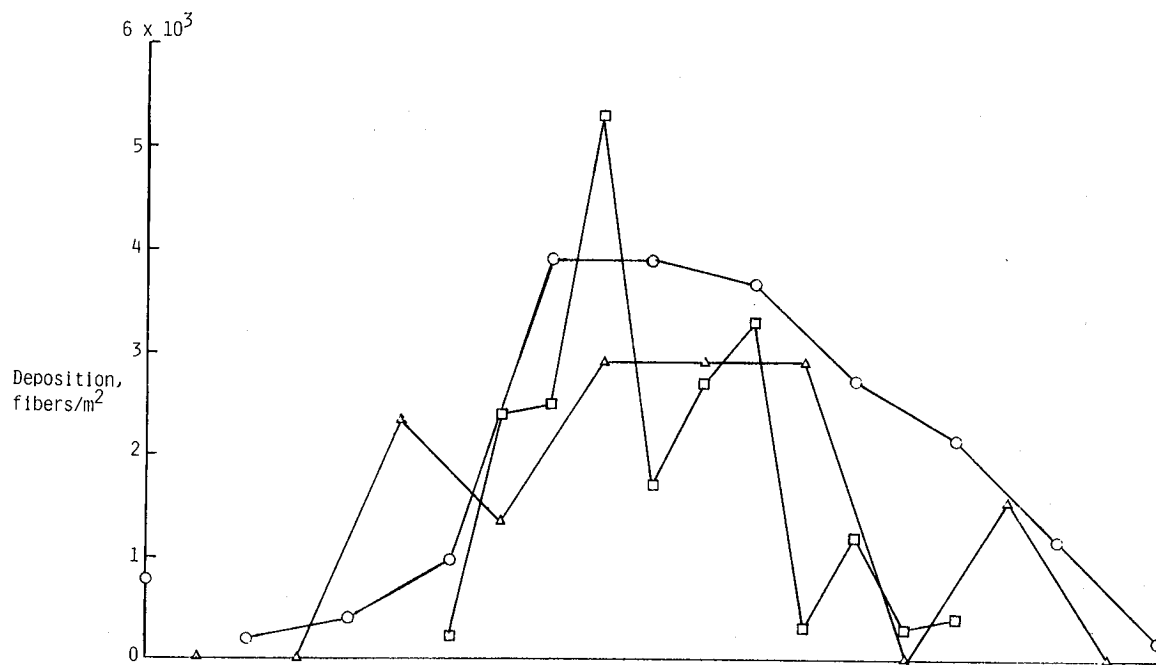


Figure 18.- Continued.

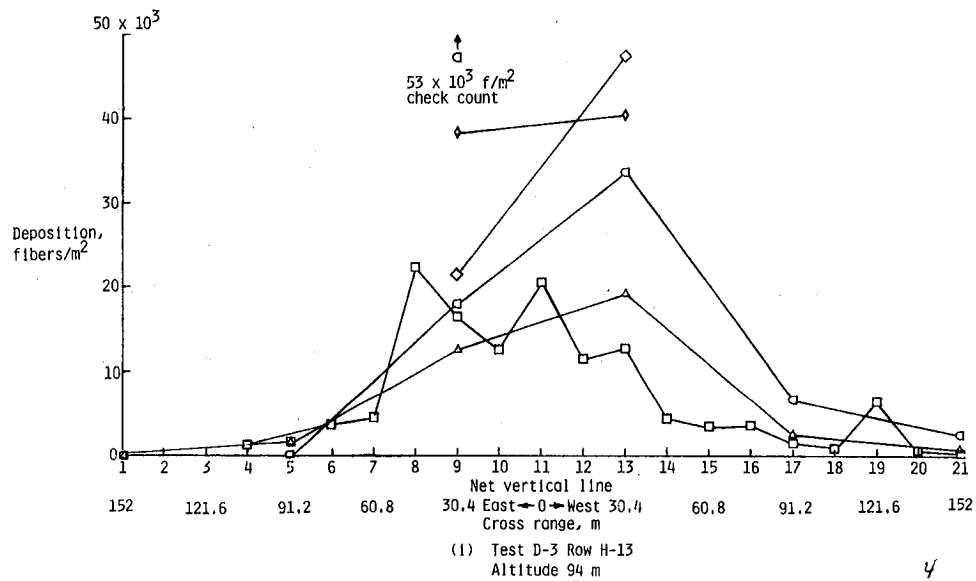
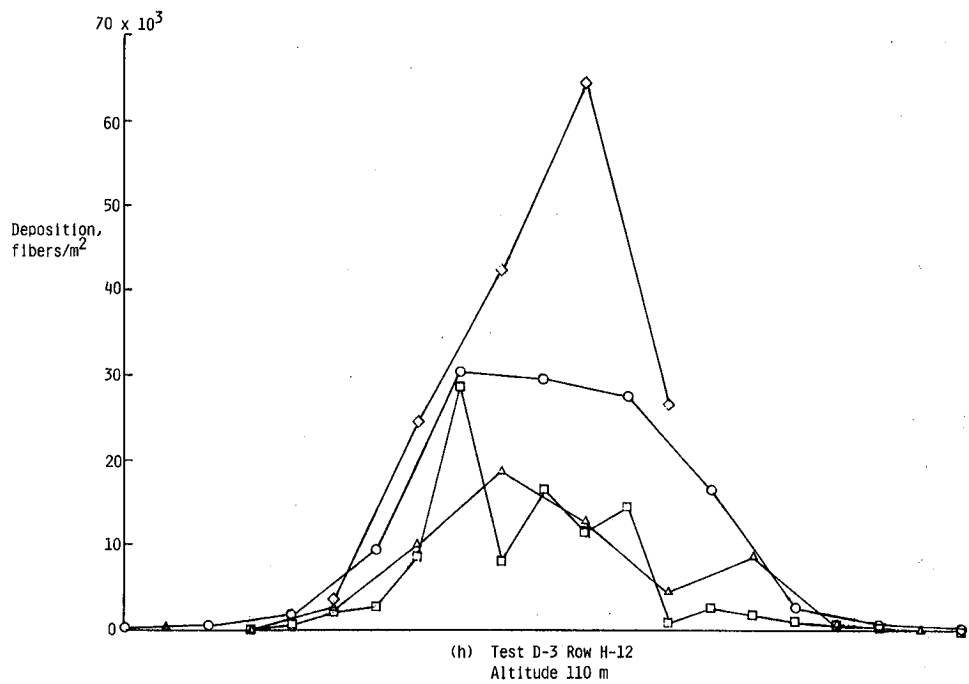
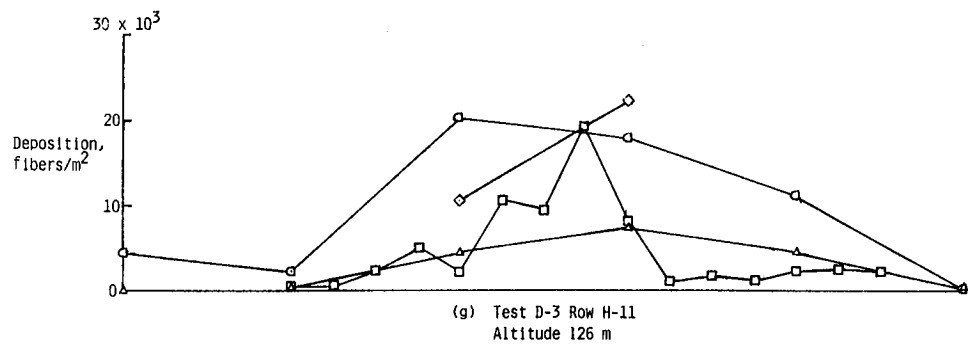


Figure 18.- Continued.

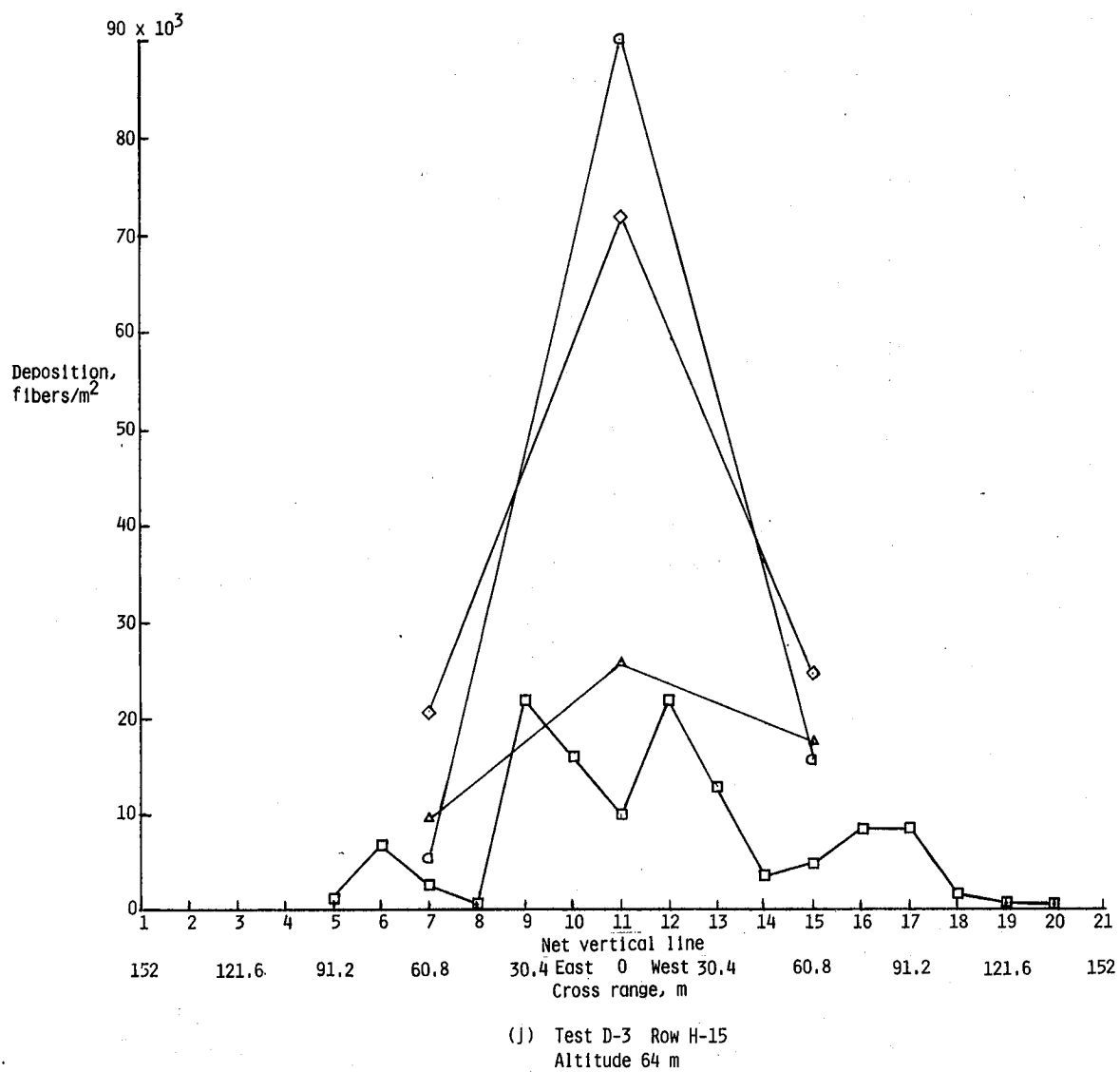
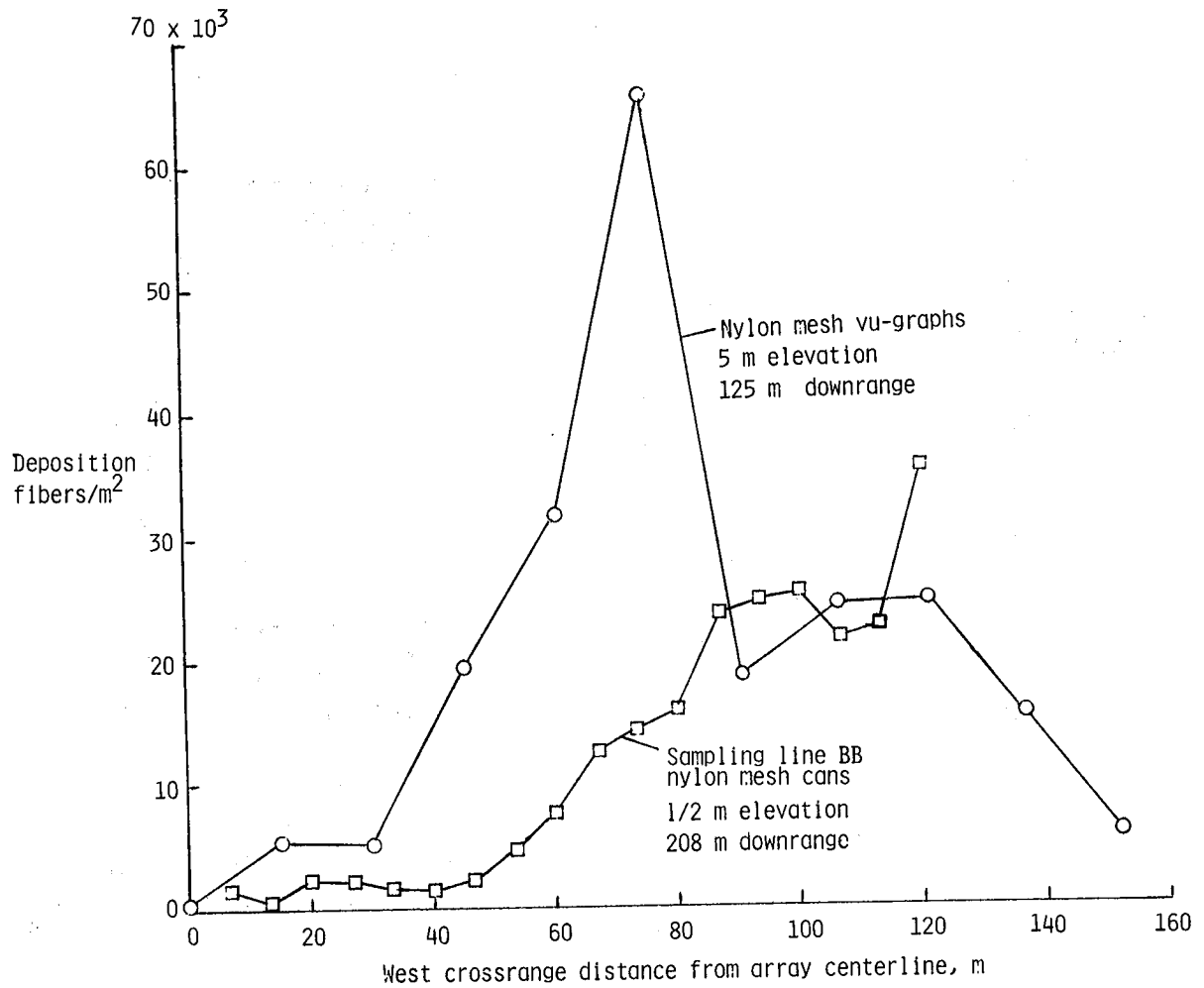
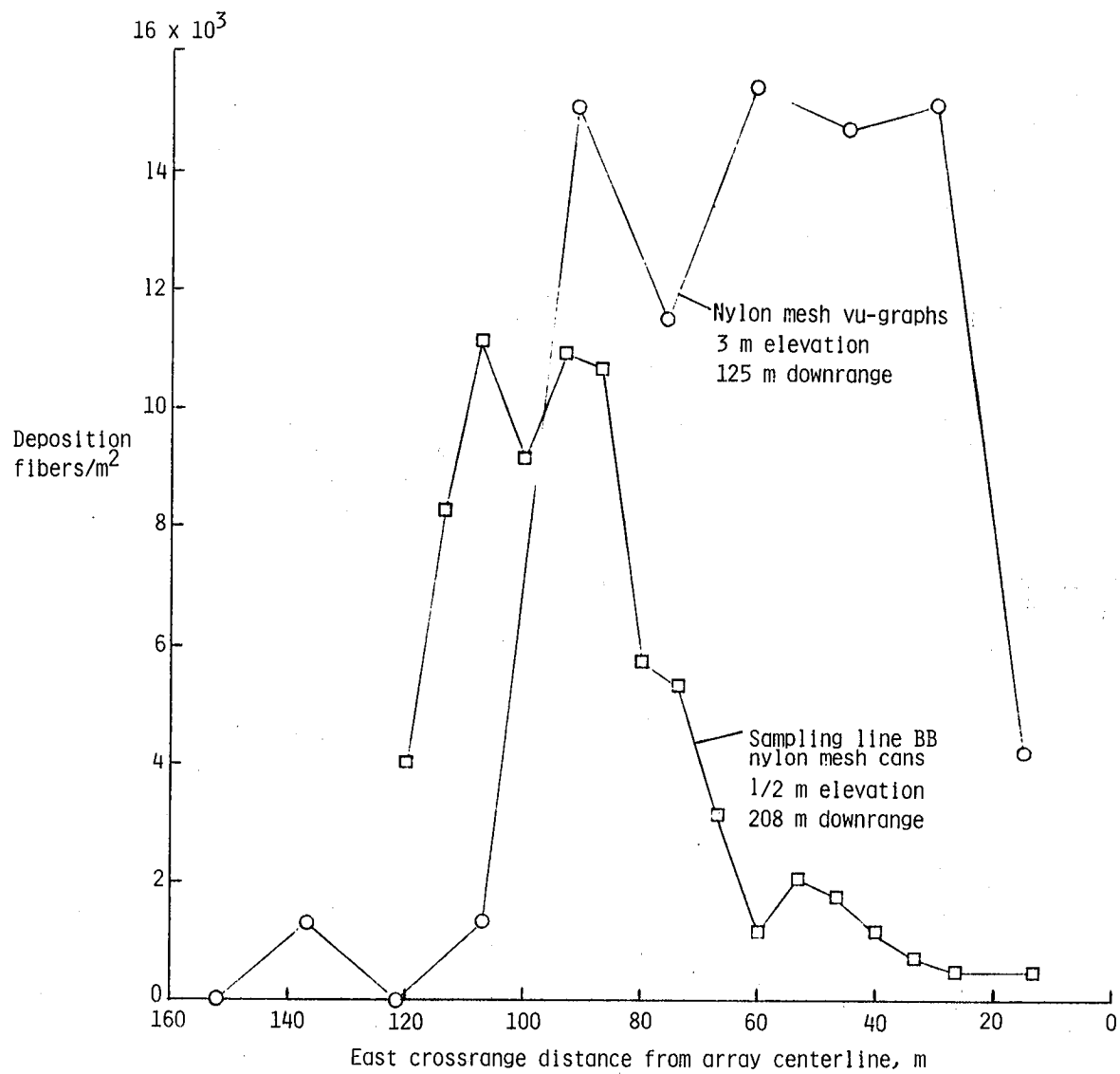


Figure 18.- Concluded.



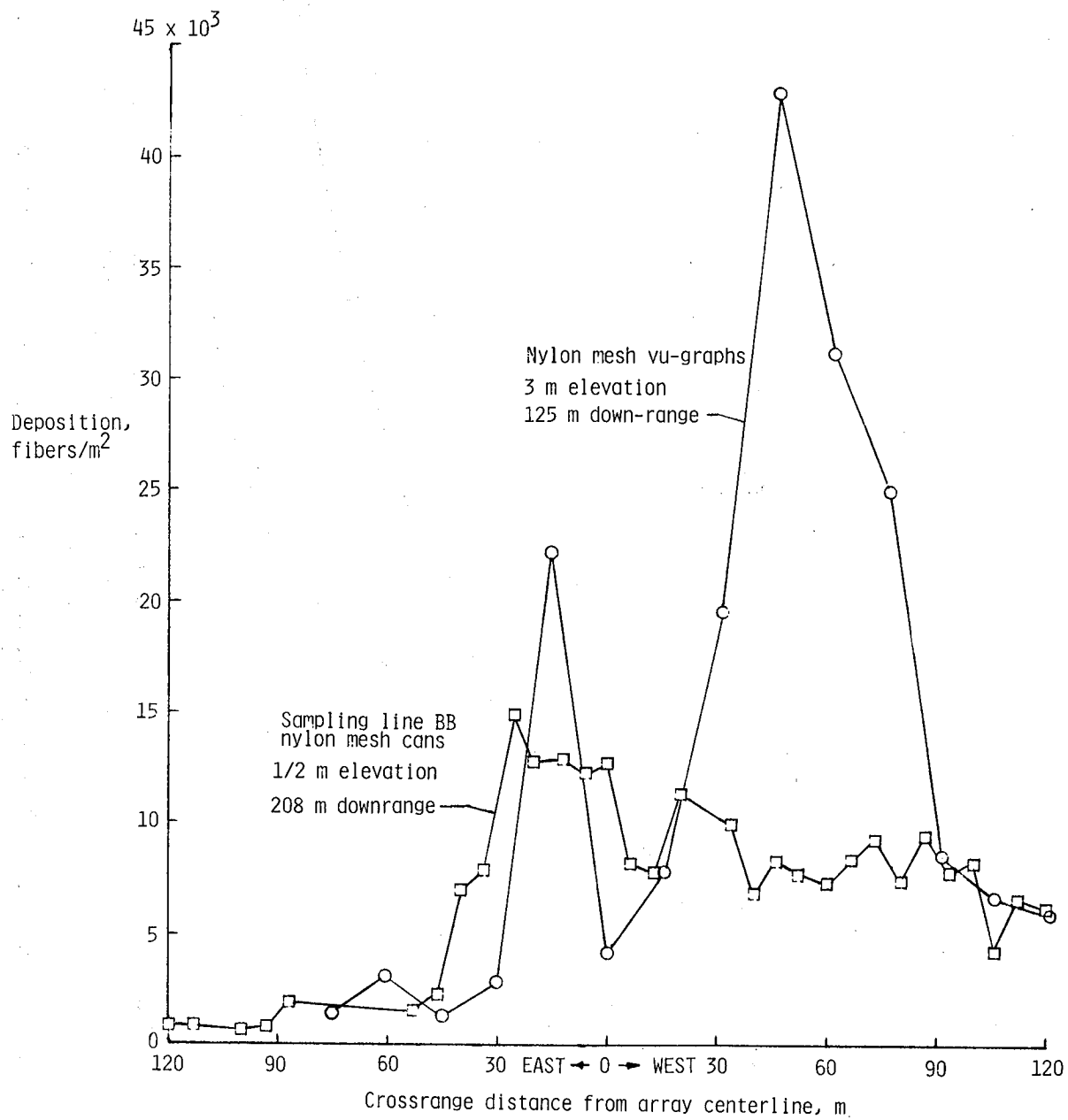
(a) Test D-1

Figure 19.- Comparison of near-ground-level deposition of single carbon fibers on vertical surfaces.



(b) Test D-2

Figure 19.- Continued.



(c) Test D-3

Figure 19.- Concluded.

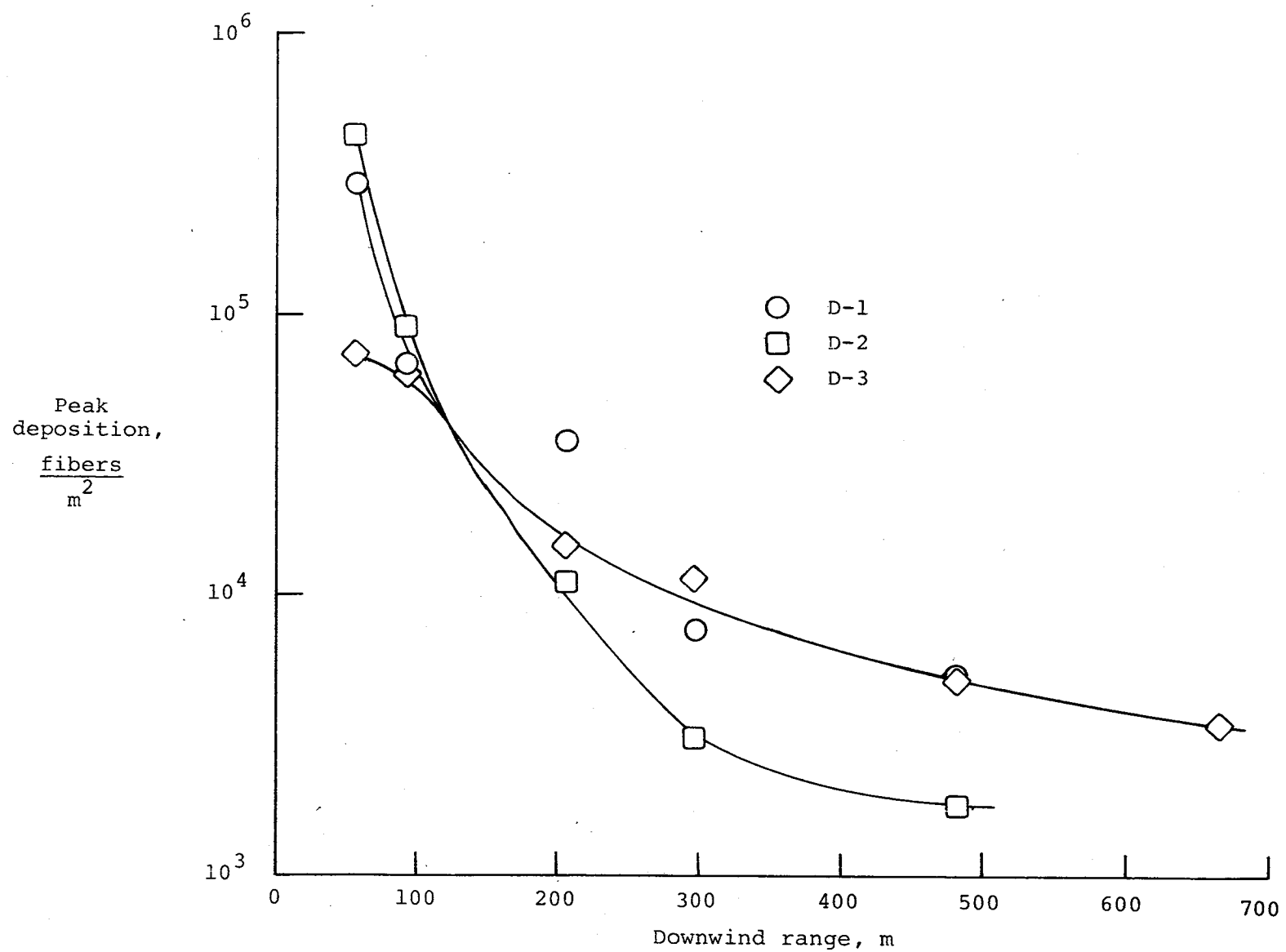


Figure 20.- Variation in peak deposition with distance downwind for vertical surface samplers 0.5m above the ground.

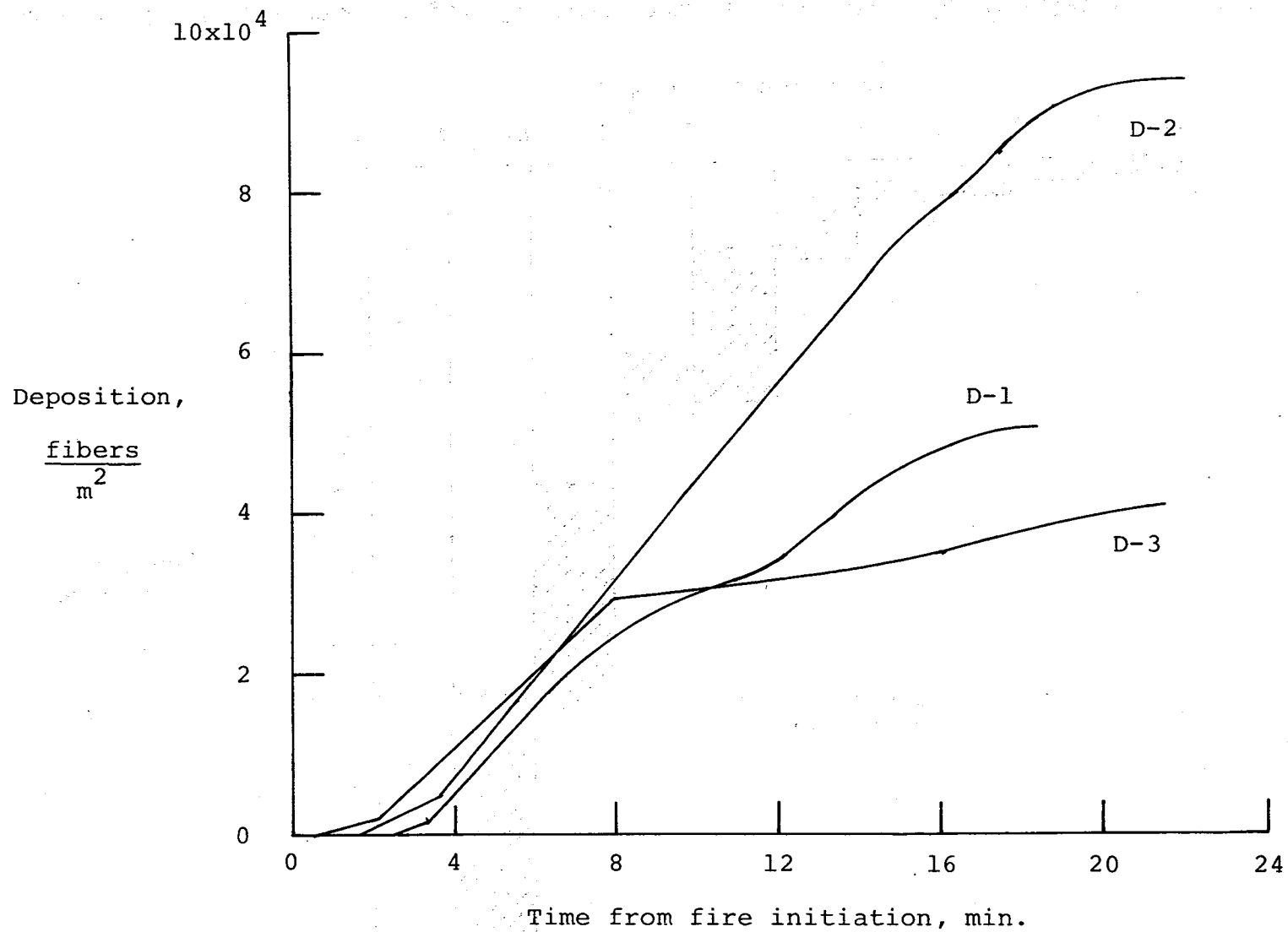


Figure 21.- Cumulative history of fibers released during burning of composite components in dissemination tests.

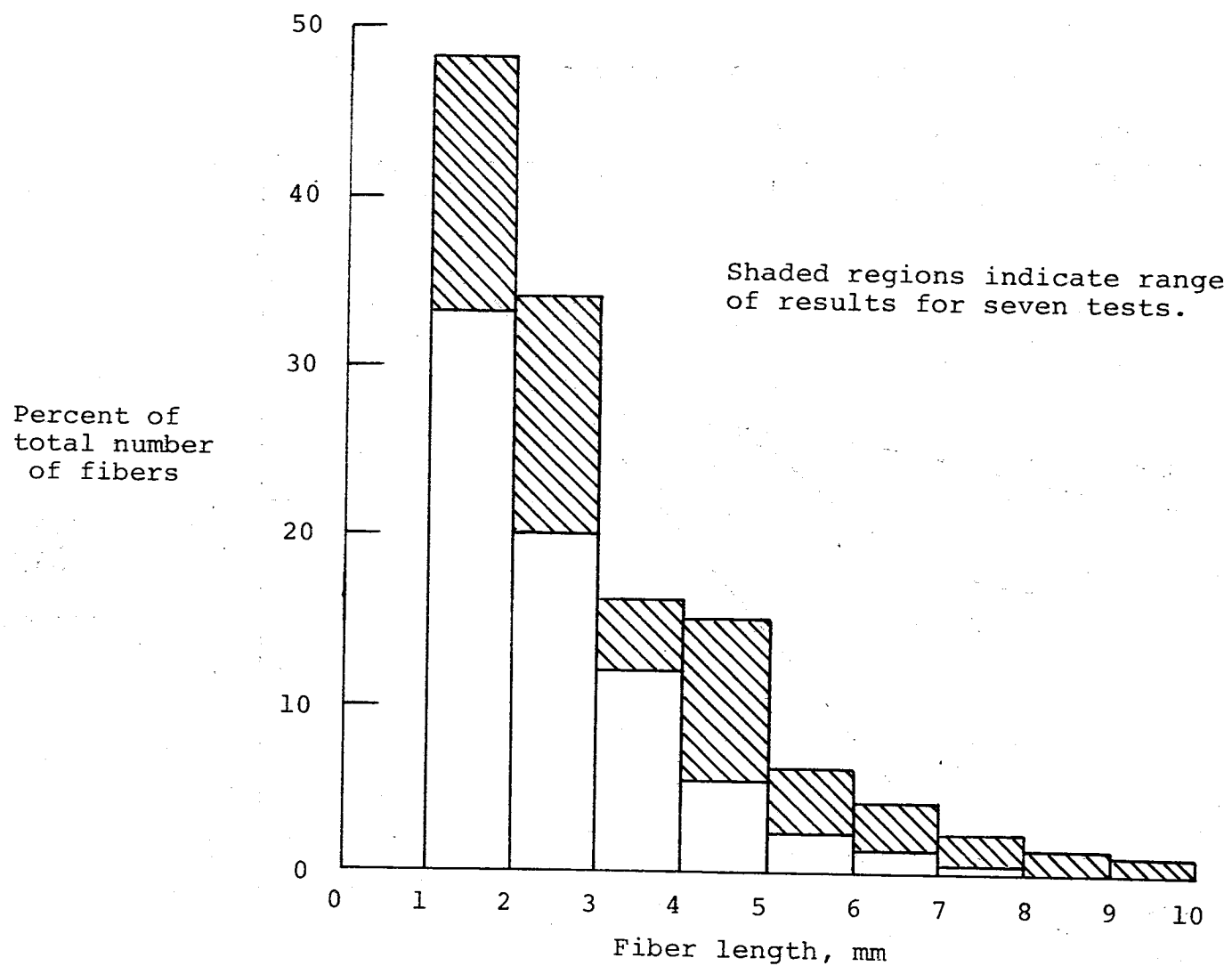


Figure 22.- Spectrum of fiber lengths for fibers greater than 1 mm in length released in outdoor aviation jet-fuel fire tests.

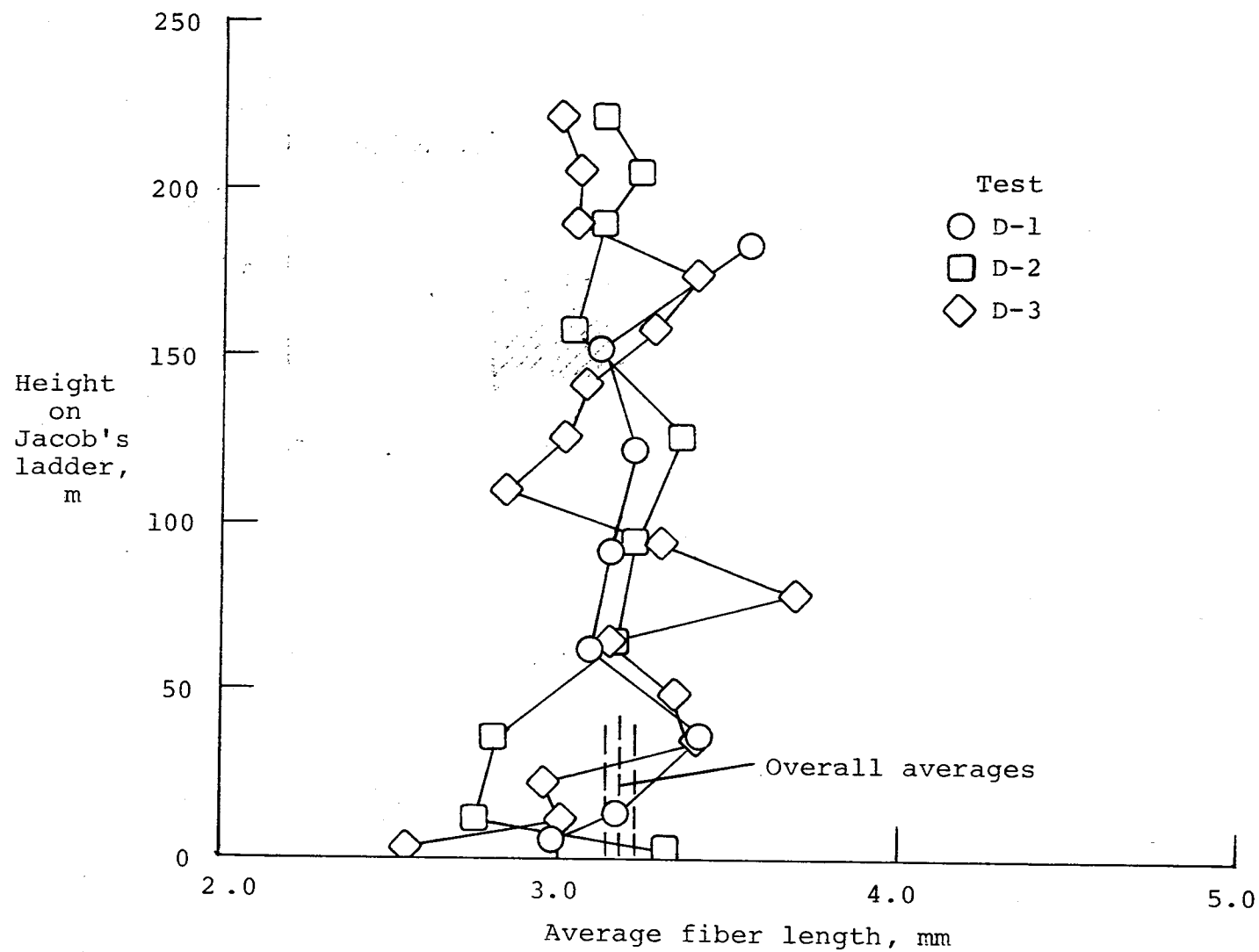


Figure 23.- Average fiber length as a function of height on the Jacob's ladder sampling net.

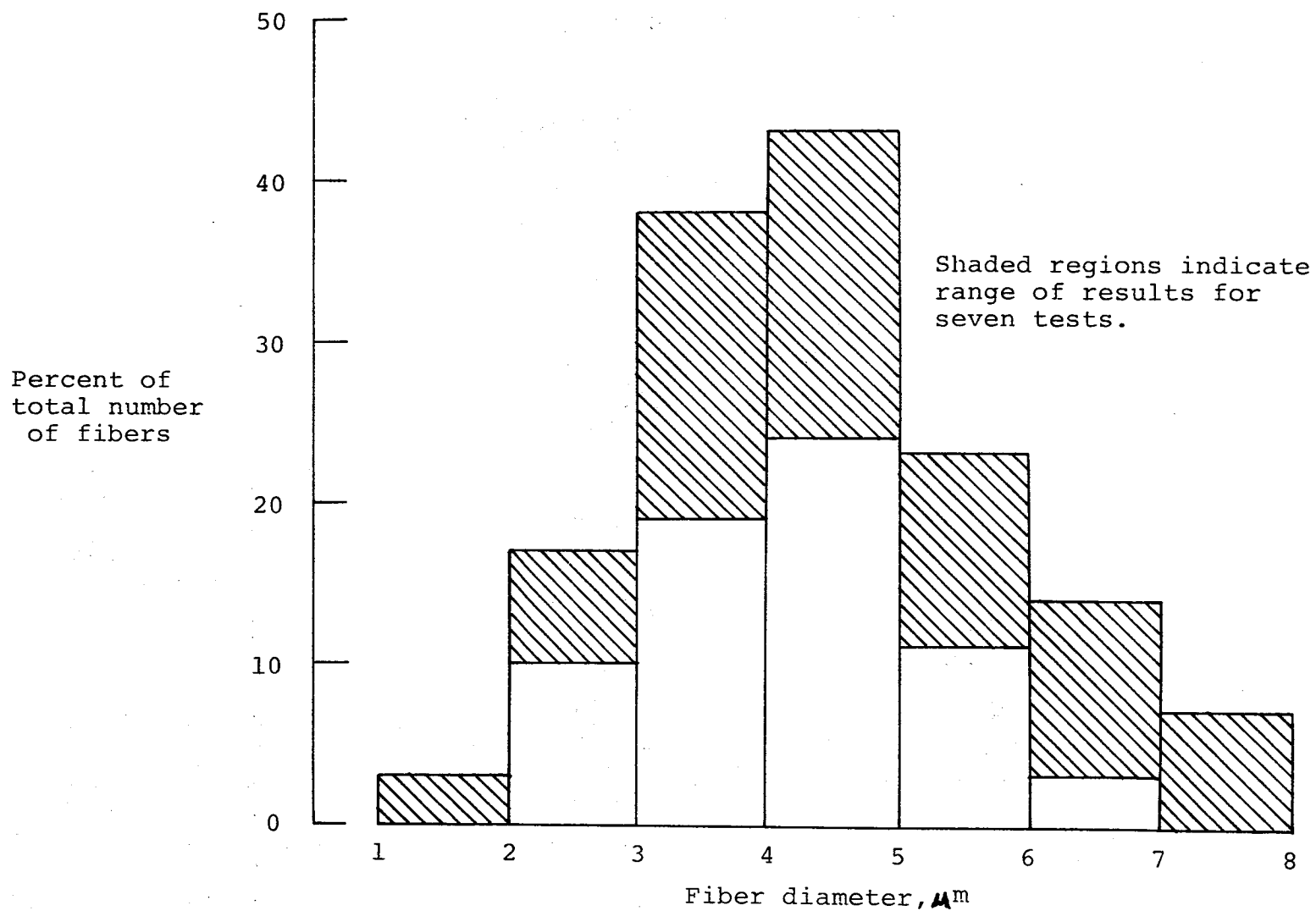


Figure 24.- Spectrum of fiber diameters for fibers greater than 1 mm in length released in outdoor aviation jet-fuel fire tests.

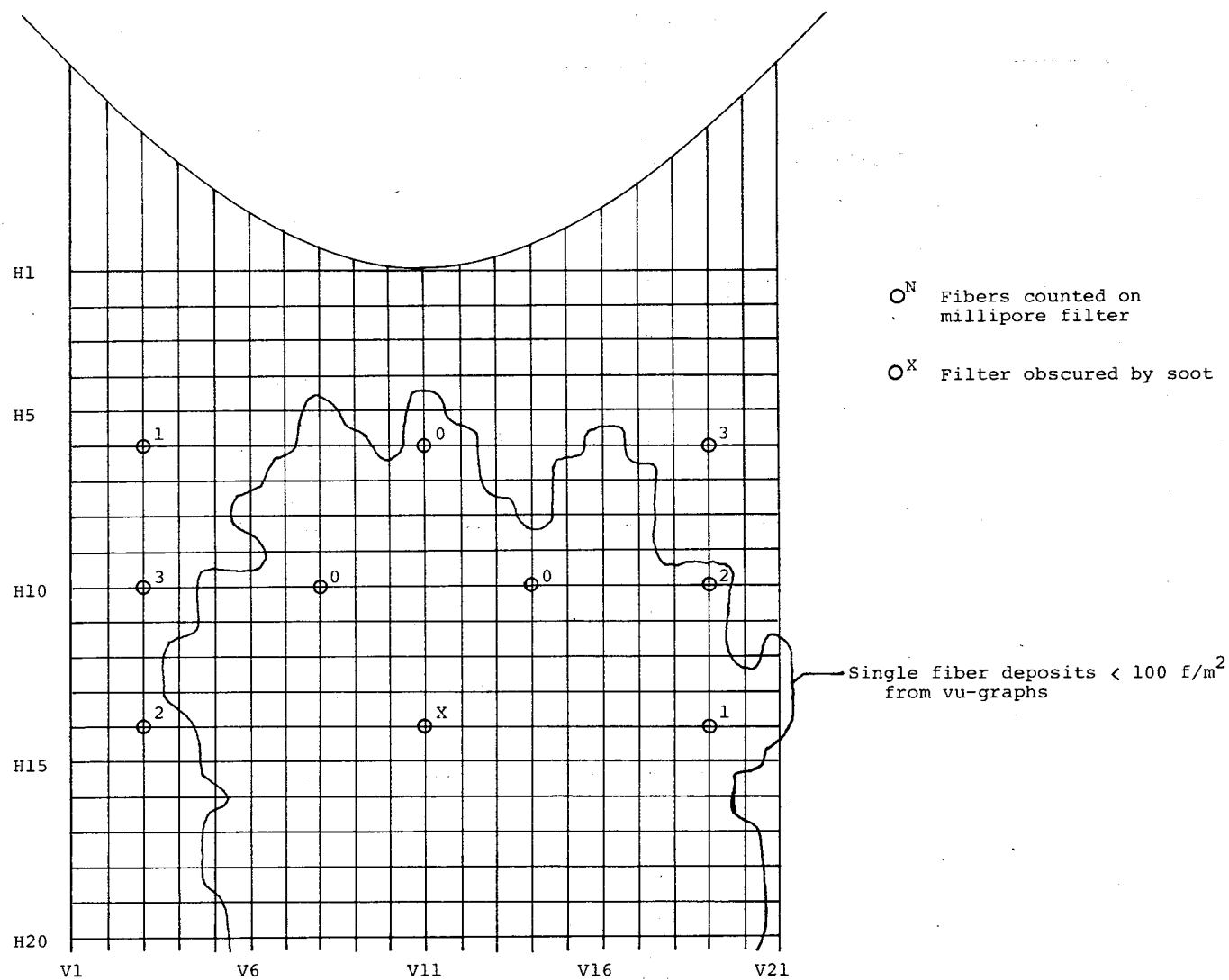


Figure 25.- NIOSH-counted small fibers from millipore filter samplers on Jacob's ladder, test D-3.

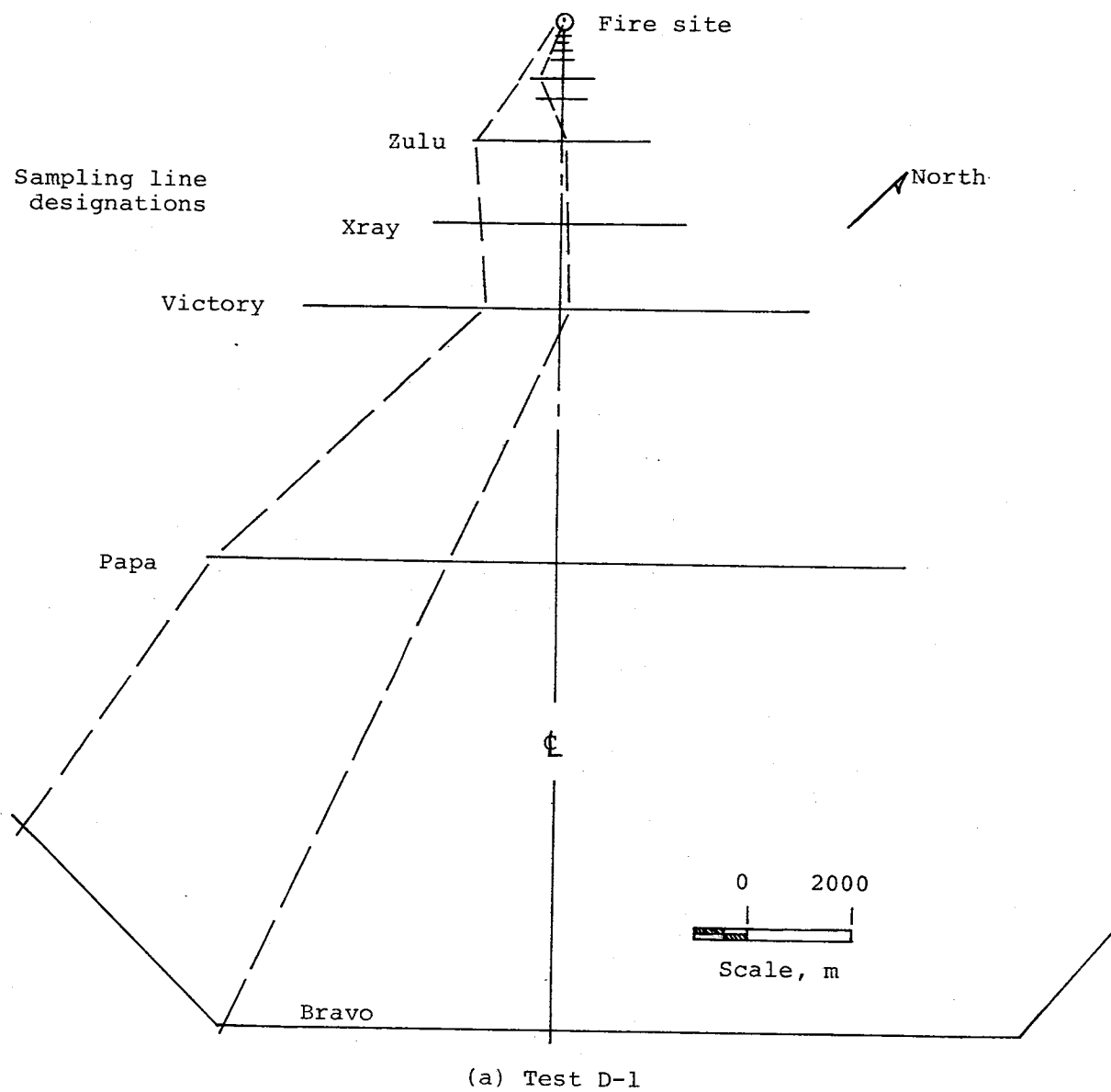
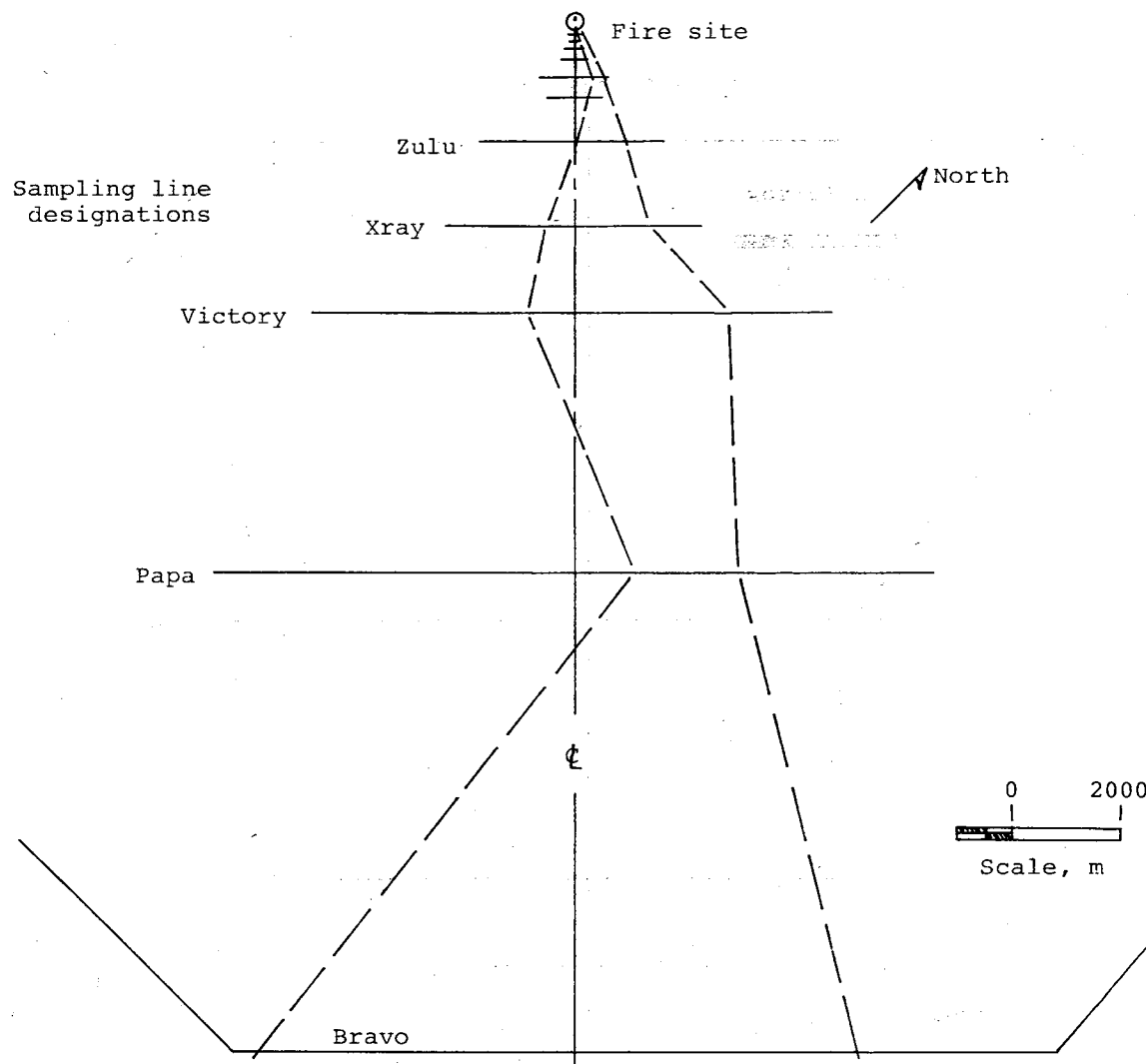
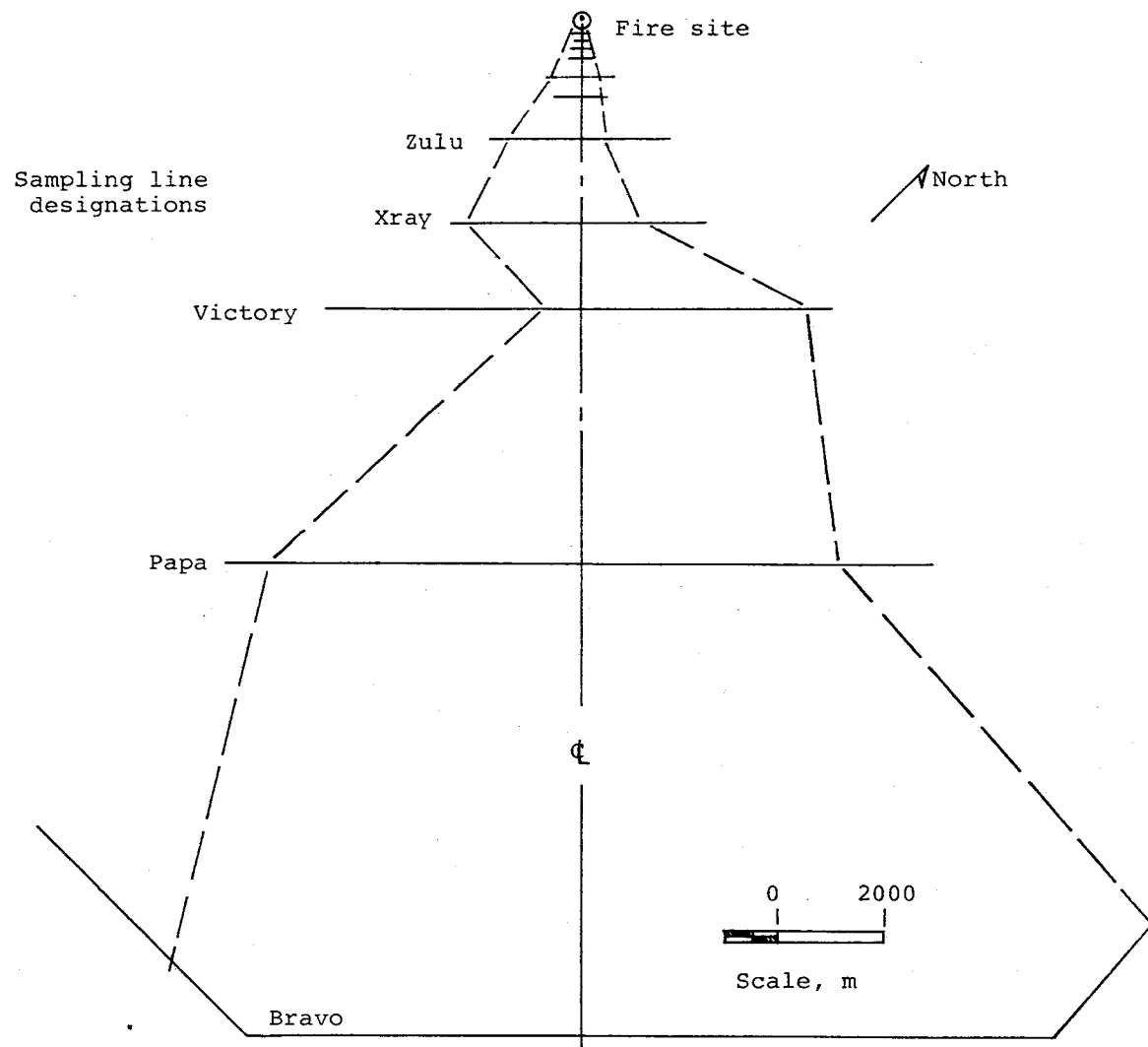


Figure 26.- Footprint of fiber deposition downwind to 19.1 km.



(b) Test D-2

Figure 26.- Continued.



(c) Test D-3

Figure 26.- Concluded.

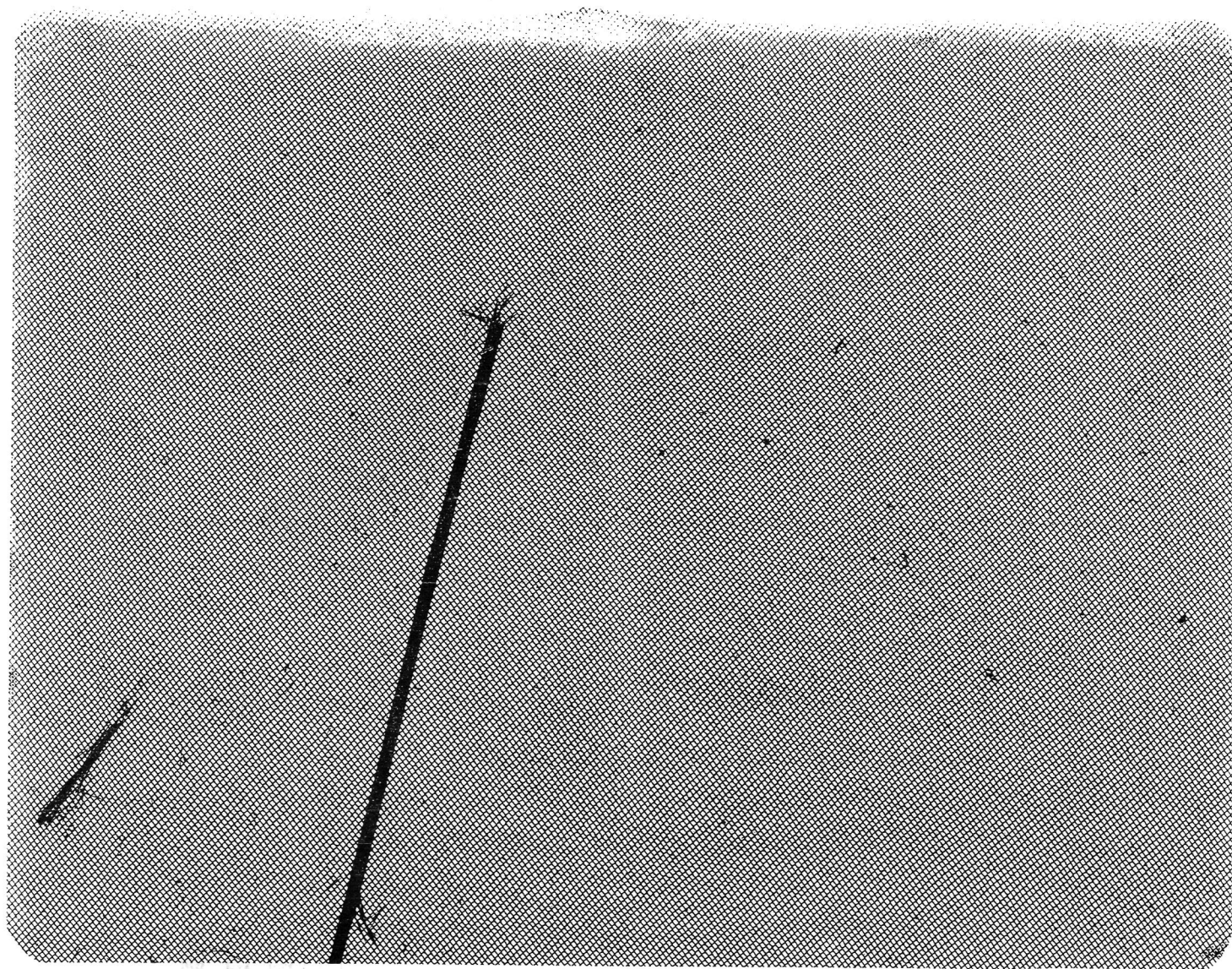


Figure 27.- Two strips of carbon-fiber composite deposited on Jacob's ladder nylon mesh vu-graph during dissemination test D-3.

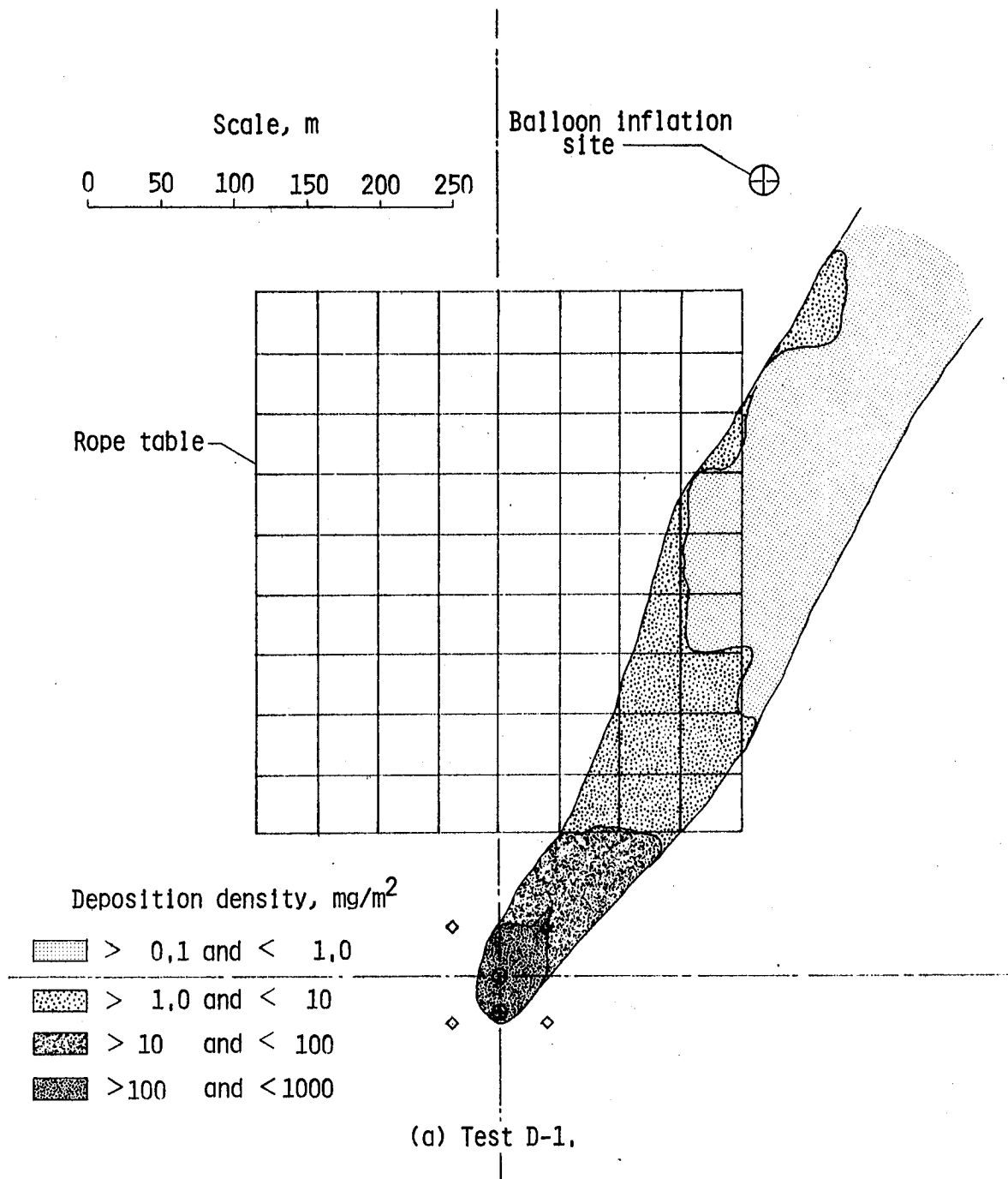


Figure 28.- Ground deposition pattern of composite strips delaminated from composite specimens in the aviation jet fuel fires.

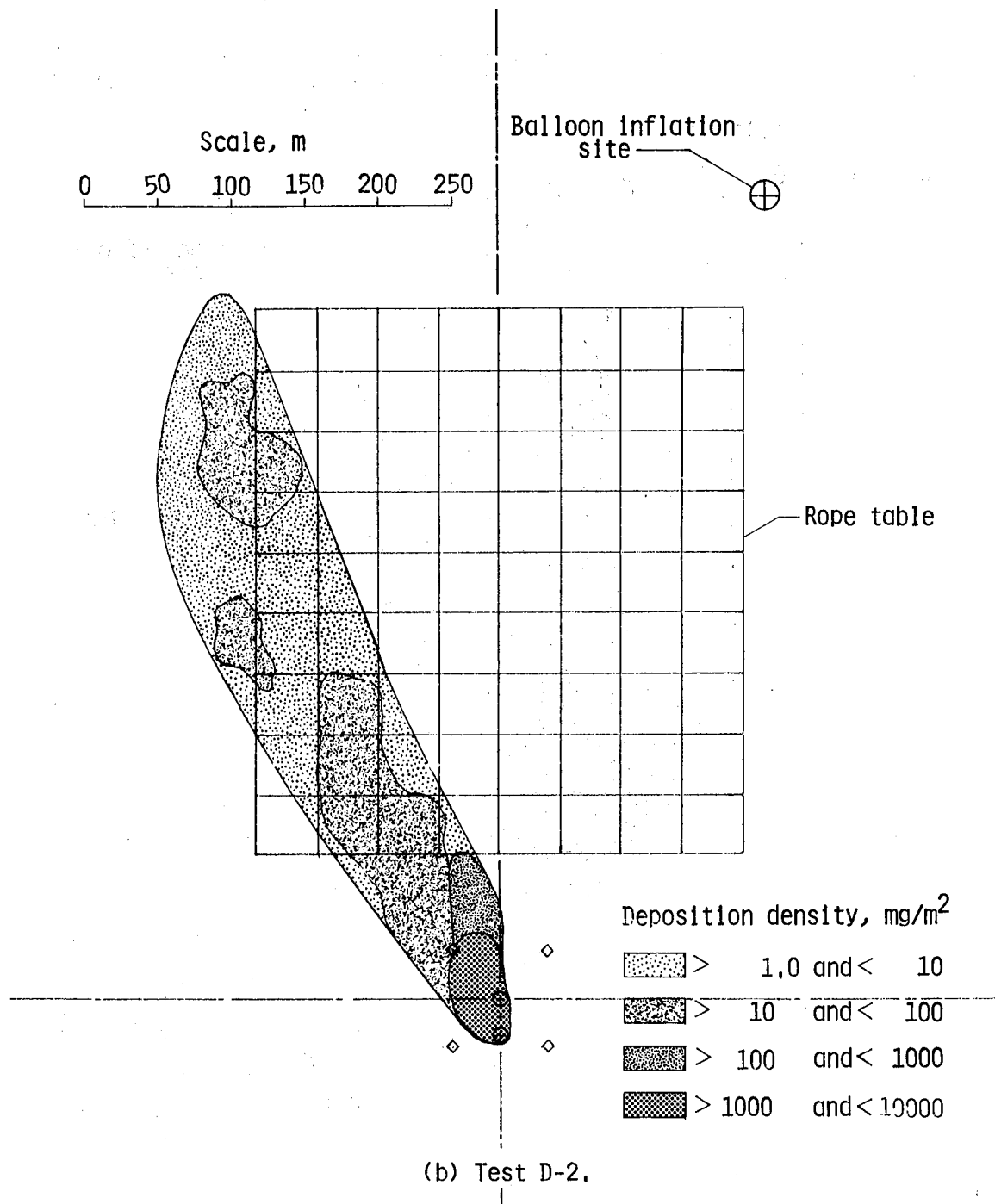


Figure 28.- Continued.

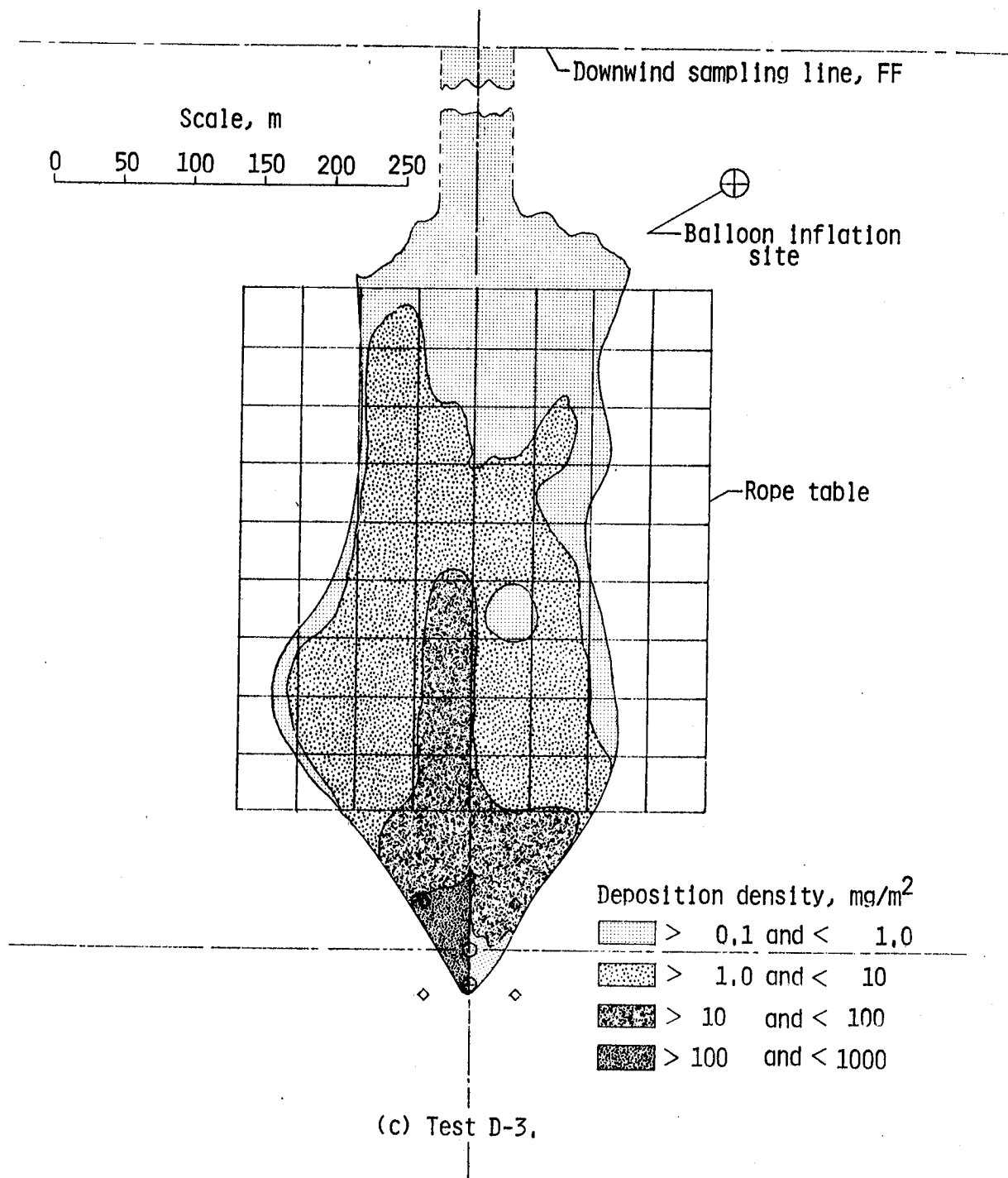


Figure 28.- Continued.

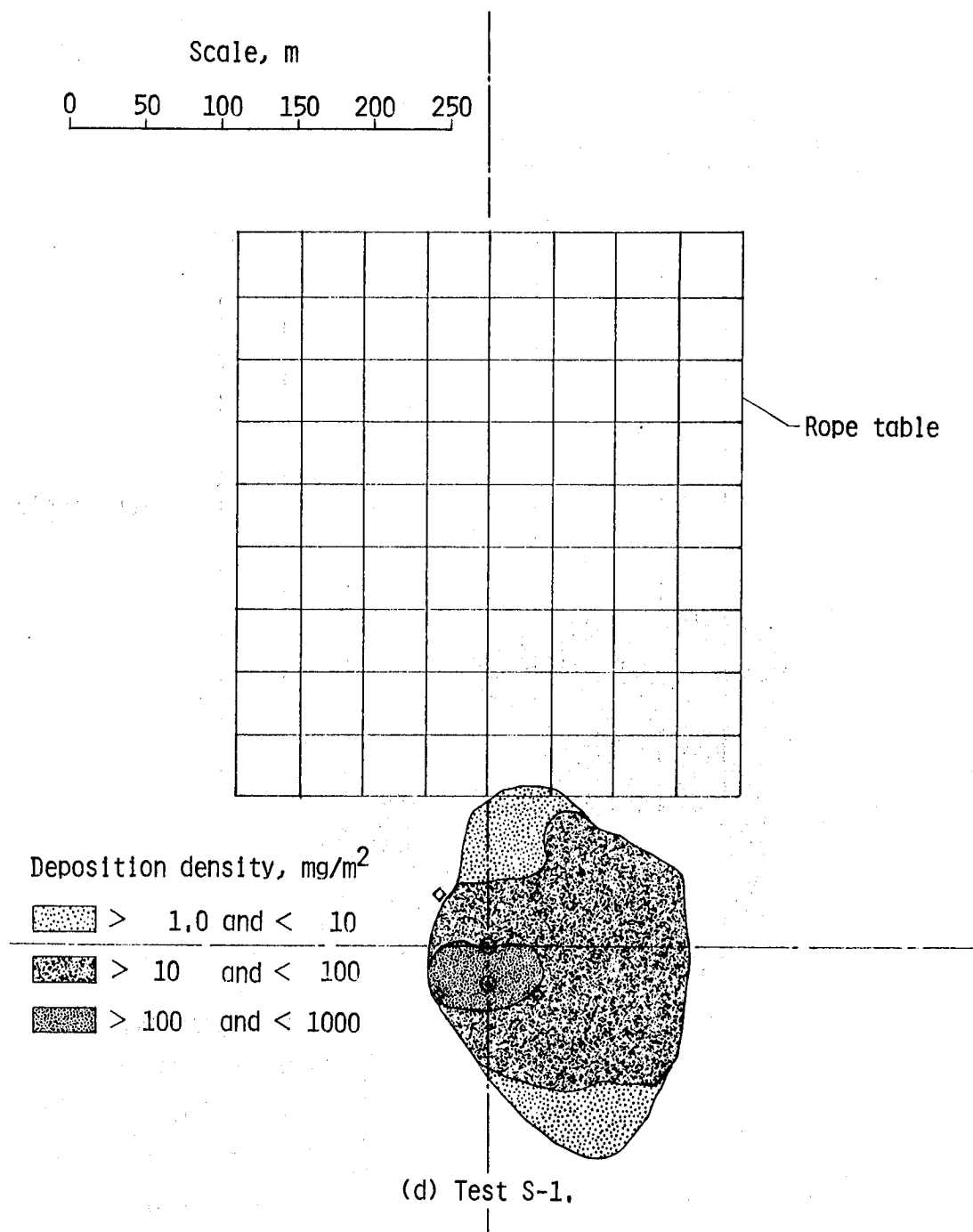


Figure 28.- Continued.

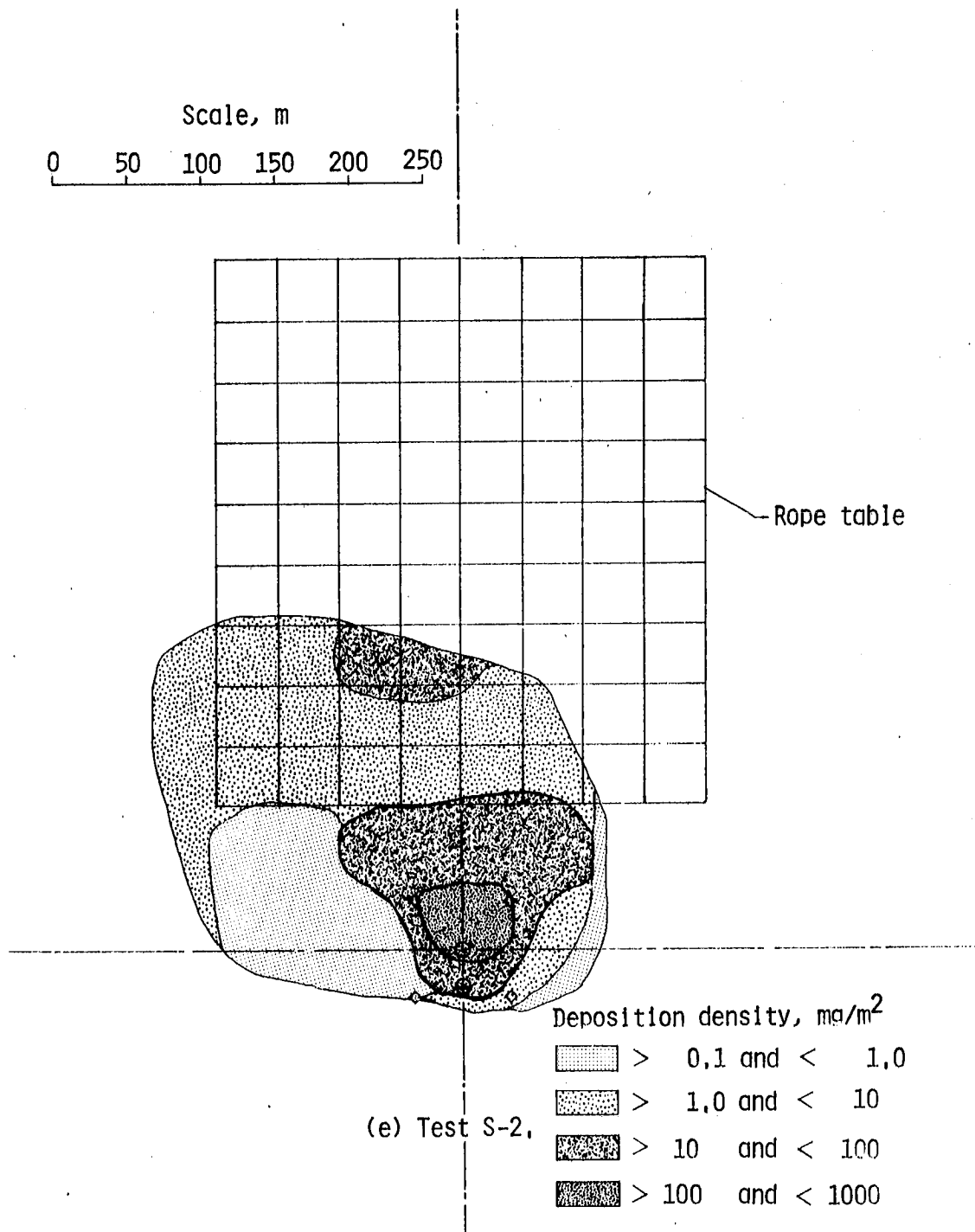


Figure 28.- Concluded.

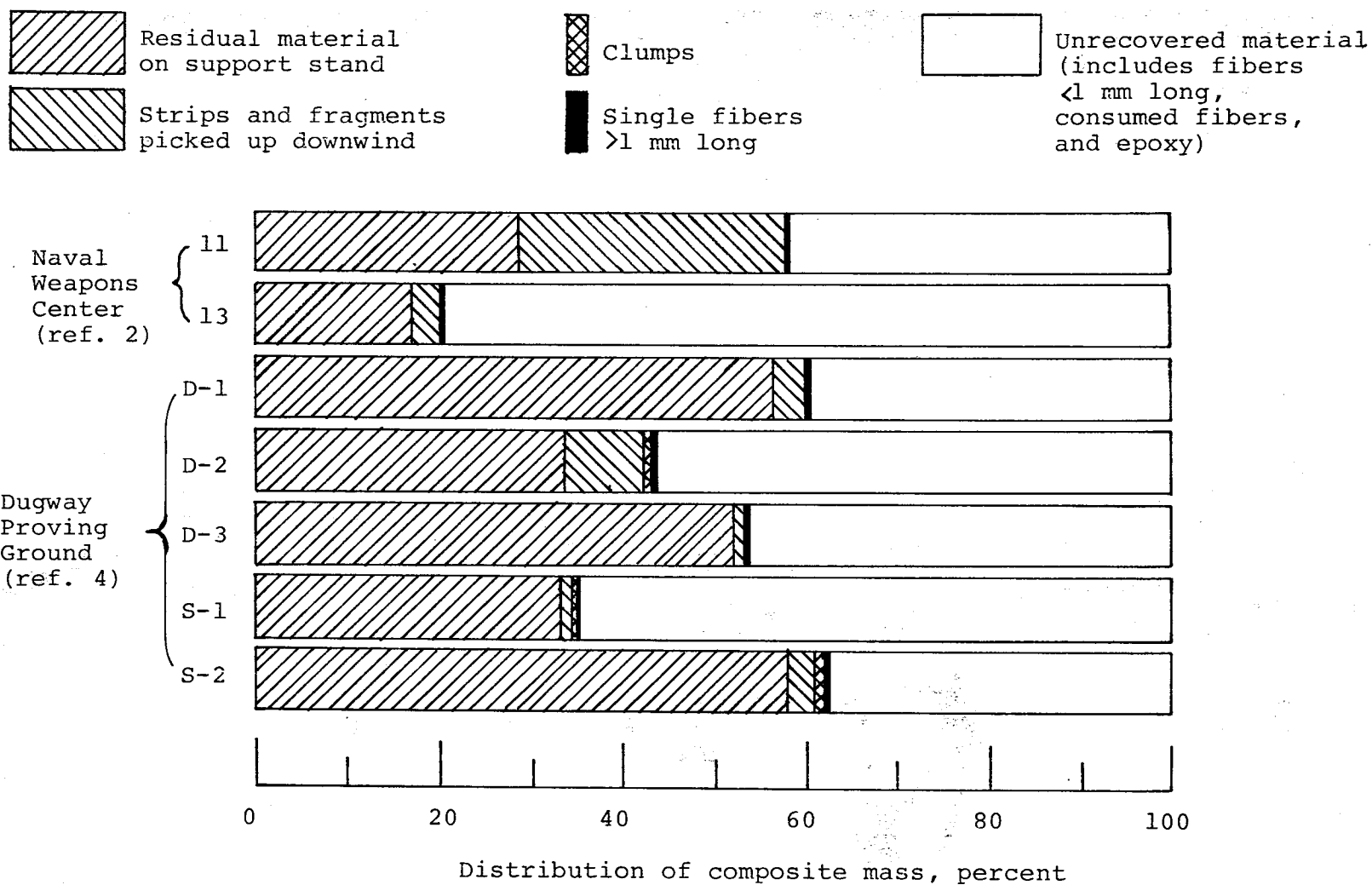


Figure 29.- Mass balance analysis of the composite materials burned in aviation jet fuel fire tests.



Figure 30.- Carbon fiber residue from burned aircraft stabilizer, test D-3.

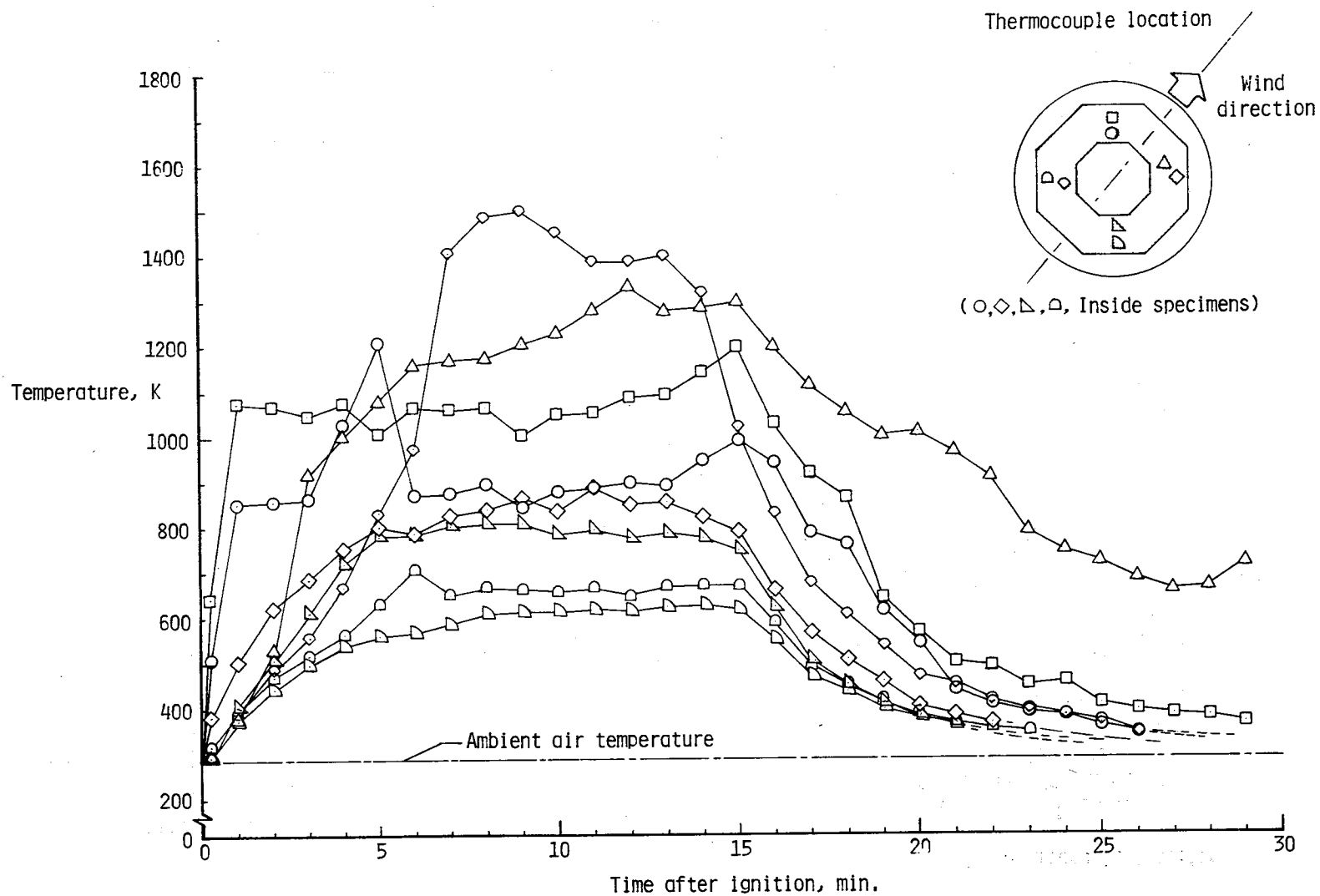


Figure 31.- Temperatures measured in the flames and inside composite specimens on the support stand for JP-4 jet fuel pool fire test D-1.

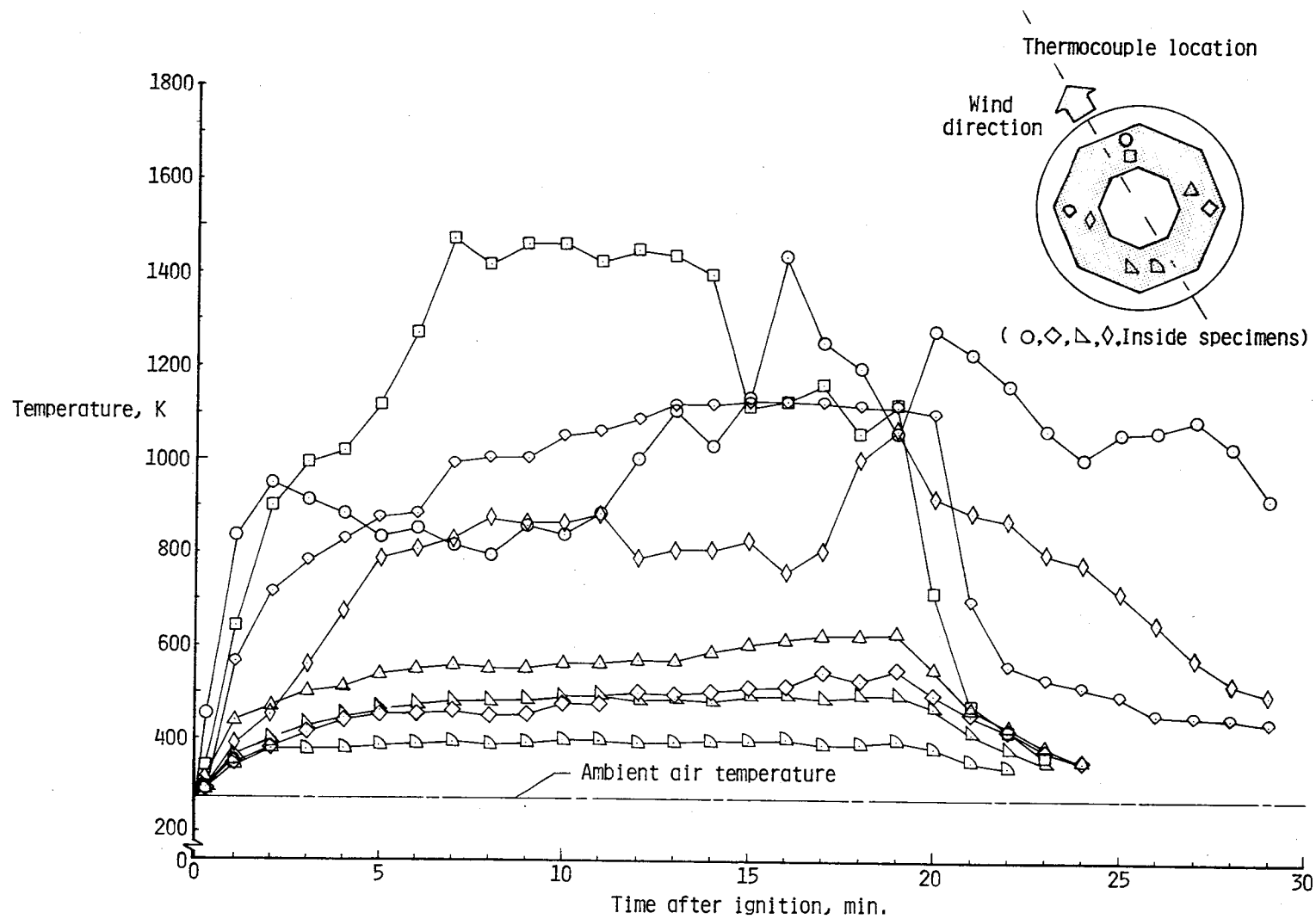


Figure 32.- Temperatures measured in the flames and inside composite specimens on the support stand for JP-4 jet fuel pool fire test D-2.

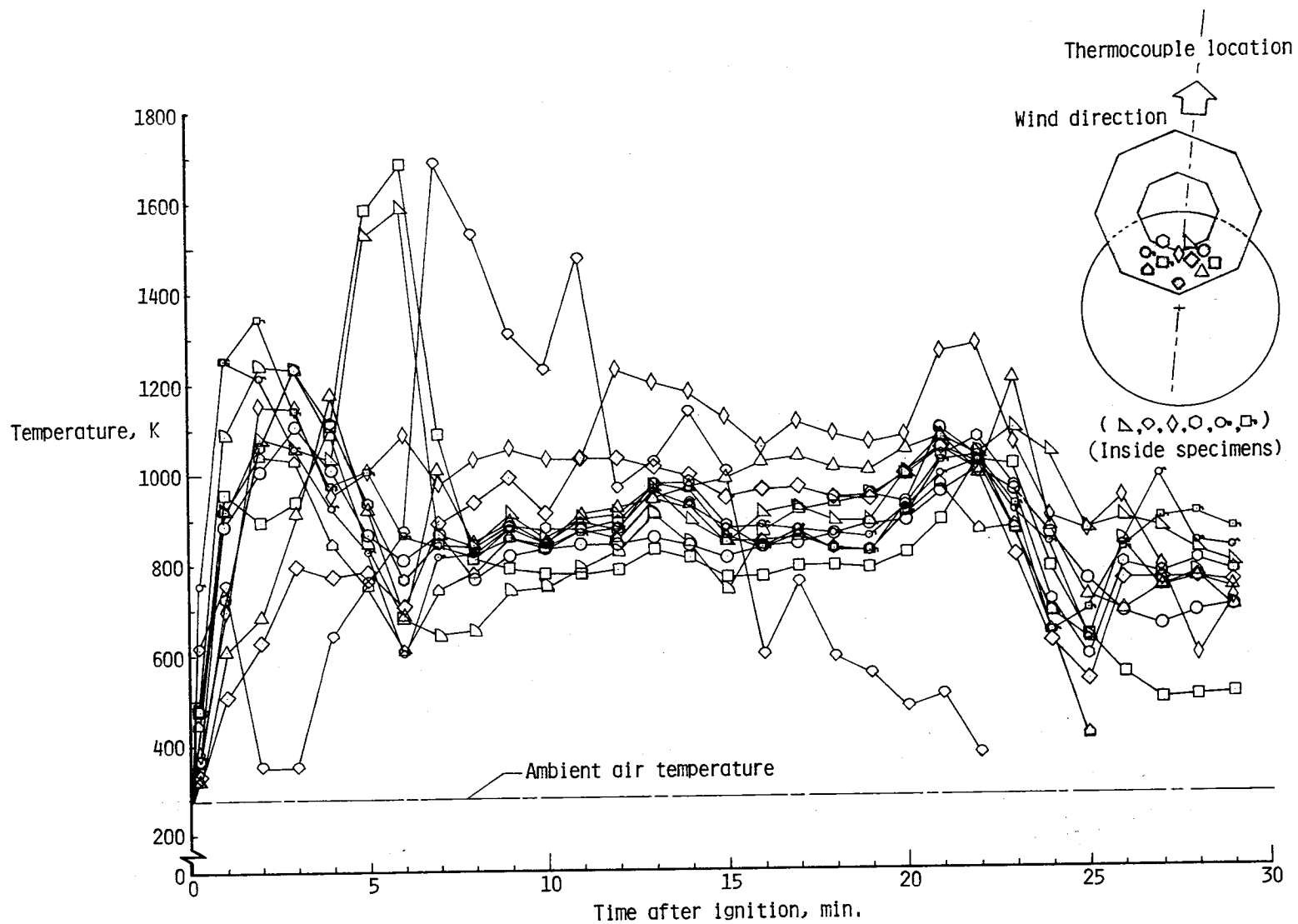


Figure 33.- Temperatures measured in the flames and inside composite specimens on the support stand for JP-4 jet fuel pool fire test D-3.

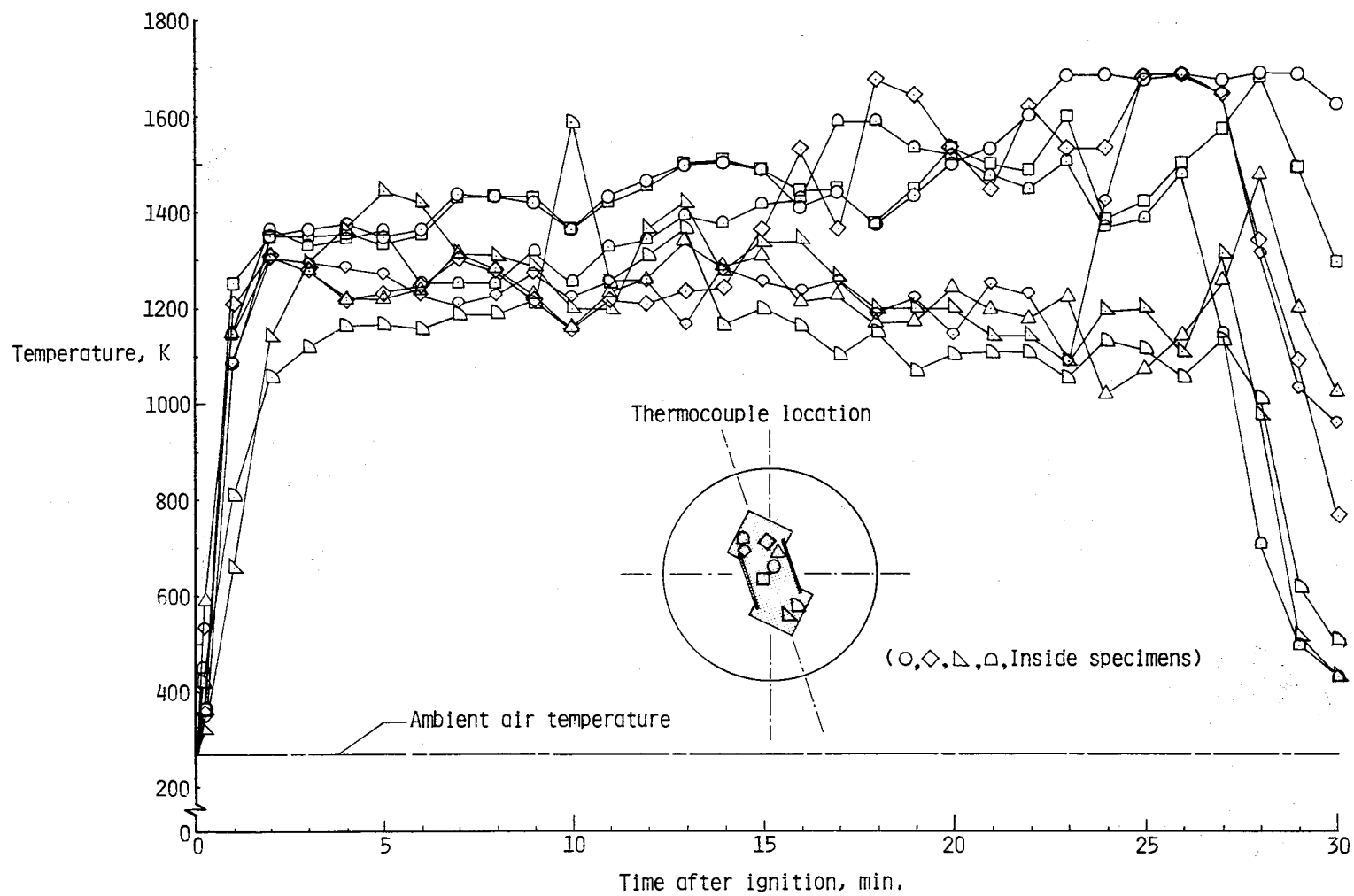


Figure 34.- Temperatures measured in the flames and inside composite specimens on the support stand for JP-4 jet fuel pool fire test S-1.

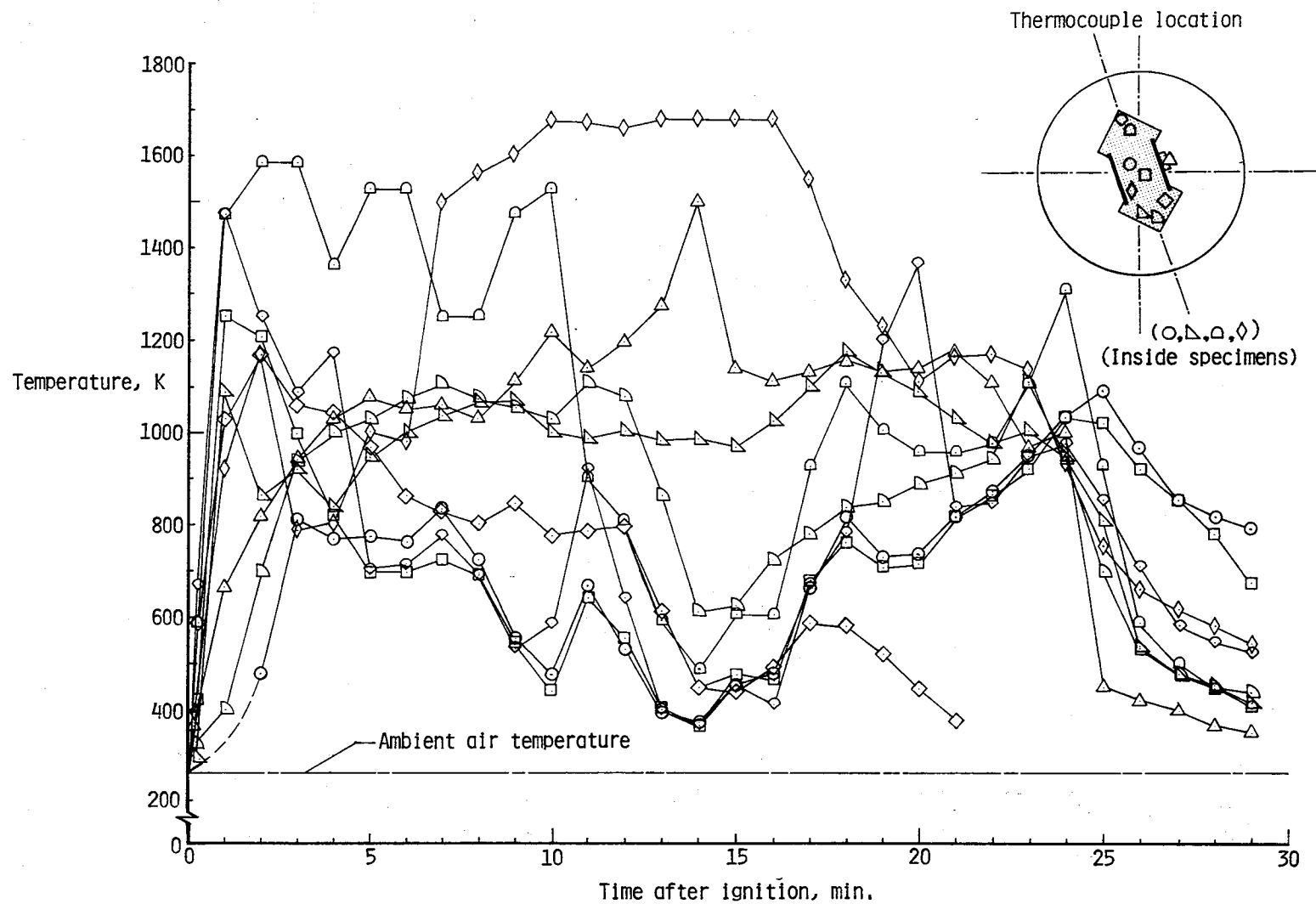


Figure 35.- Temperatures measured in the flames and inside composite specimens on the support stand for JP-4 jet fuel pool fire tests S-2.

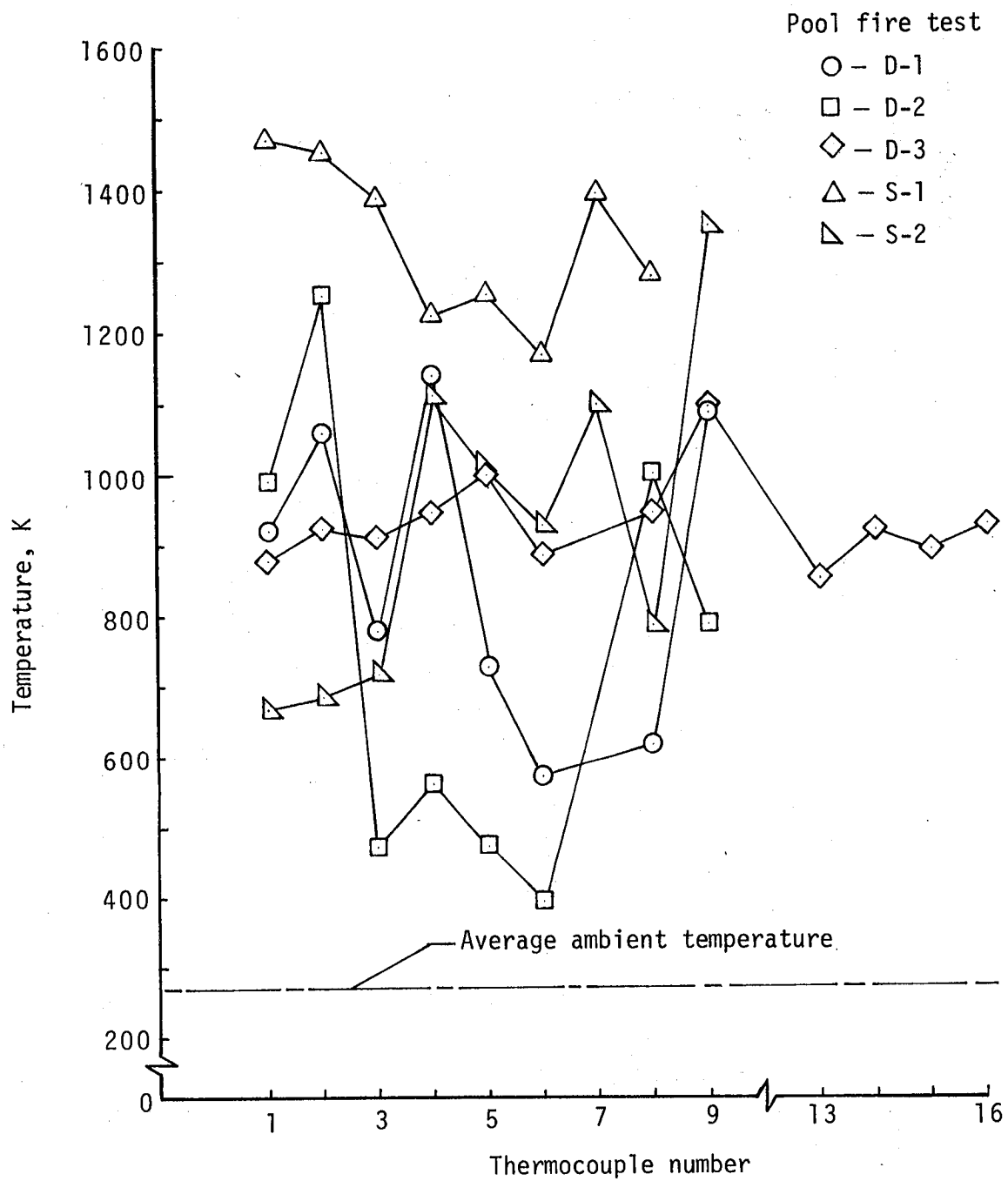


Figure 36.- Average temperatures measured on the specimen support stand for the total burn time.

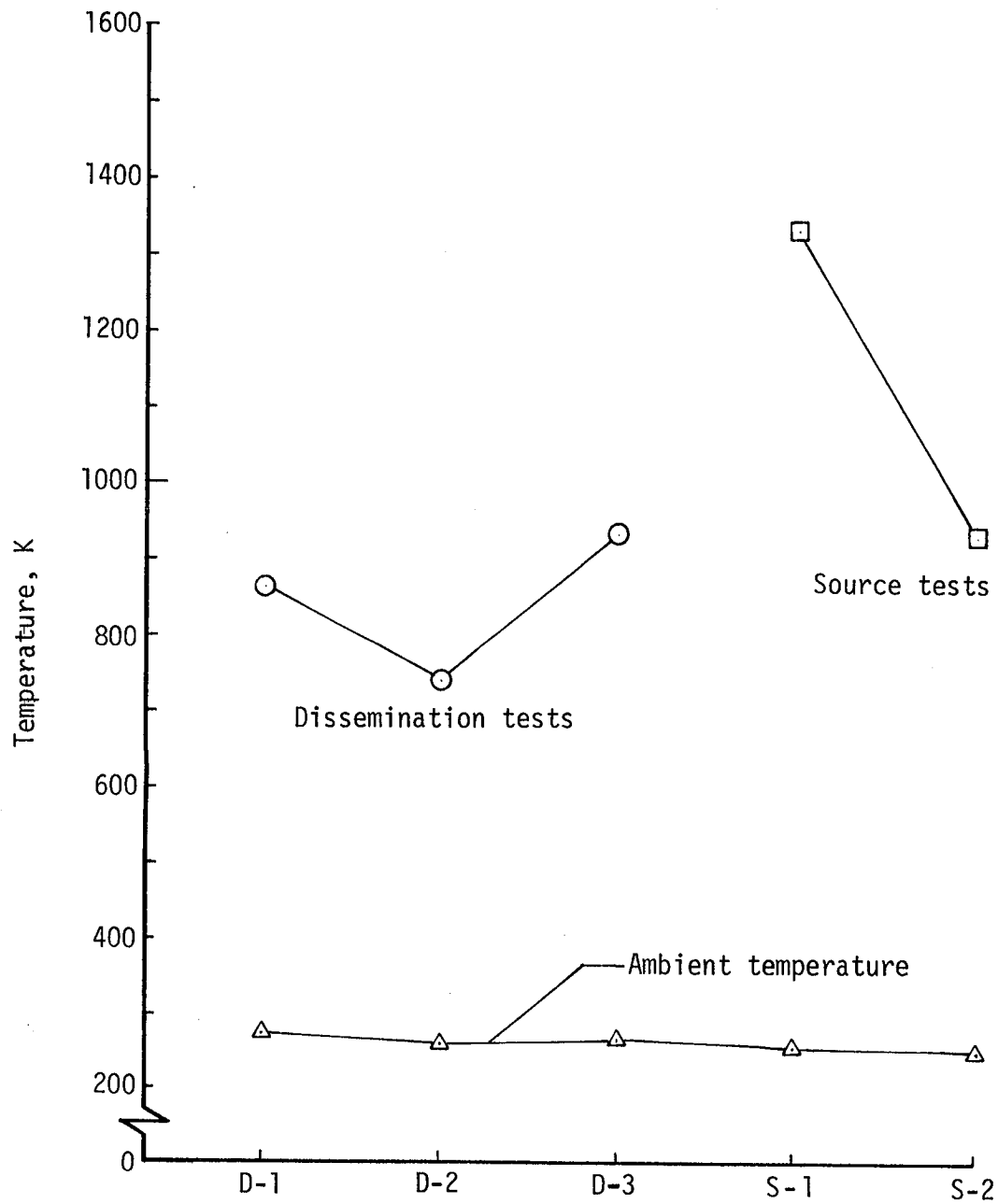


Figure 37.- Average measured temperature from all thermocouples on the specimen support stand for the total burn time.

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15. Supplementary Notes					
16. Abstract <p>A realistic release of carbon fibers was established by burning a minimum of 45 kg of carbon-fiber composite aircraft structural components in each of five large-scale, outdoor aviation jet fuel fire tests conducted at the U.S. Army Dugway Proving Ground, Utah. This release was quantified by several independent assessments with various instruments developed specifically for these tests. The most likely values for the mass of single carbon fibers released ranged from 0.2 percent of the initial mass of carbon fiber for the source tests (zero wind velocity) to a maximum of 0.6 percent of the initial carbon fiber mass for dissemination tests (5-6 m/s wind velocity). Mean fiber lengths for fibers greater than 1 mm in length ranged from 2.5 to 3.5 mm. Mean diameters ranged from 3.6 to 5.3 μm which was indicative of significant oxidation. Footprints of downwind dissemination of the fire-released fibers were measured to 19.1 km from the fire. The tests demonstrated a reasonable validation of the assumed carbon fiber lengths and quantity released that were used in the NASA risk assessment.</p>					
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